SPACE

MARTIN INCE

An overview: from the first Sputnik to the 'brave new world' of the future

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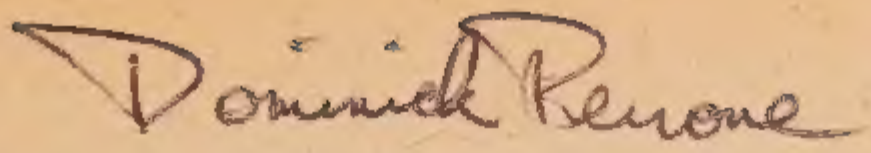

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This is his first book.

SPACE

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For Victoria

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1 Introduction

The world of space is close at hand. It starts, by one definition, just 100 kilometres above our heads. The vast bulk of the Earth's atmosphere is below that altitude. For all practical and most philosophical purposes, space goes on for ever. Before 1957, when the first spacecraft were sent above the Earth's atmosphere and into orbit around the Earth, space was almost an unknown to scientists. That need not be any surprise. Although space is nearby – the noted British astronomer Sir Fred Hoyle points out that it is only an hour's drive away in your car if the thing could be driven vertically upwards – it is without doubt almost empty and, until recently, the matter and energy which exist there had been inaccessible to direct experiment. So, what is space like, the endless world to which we are now sending people and machines in increasing numbers?

The Earth itself is an almost spherical ball of rock with a diameter of just over 12,700 kilometres. Even allowing for the deepest tree roots, the life on its surface extends down by only about 100 metres. But the Earth's surface has another feature, unique in the solar system at the present time. This is liquid water: seas, lakes and rivers with dissolved chemicals, and of course plants and animals, in them. This water, in concert with the Earth's atmosphere, makes up a complex heat engine driven by the Sun's rays, driving the Earth's winds and ocean currents. But the winds which cause the weather we experience here at the base of the atmosphere occur mainly in the comparatively dense layers of air near the ground. Although the fierce buffets which spacecraft sometimes get from strong winds on their way through the atmosphere have been a problem for some space launches, our story begins where the air starts to run out.

Sounding rockets – small rockets which can explore the

region tens of kilometres above our heads – have mapped the structure of the region where the atmosphere turns to space, and since the space age began, their findings have been vastly amplified by satellites. One of the first scientific findings of the space age was the discovery of thick layers of charged sub-atomic particles, held in place by the Earth's lines of magnetic force. These belts were discovered in 1958 and called the Van Allen belts after James Van Allen, the US space scientist whose experiments sniffed them out.

The Van Allen belts start a few hundred kilometres above the Earth's surface and go on for up to 50,000 km, about an eighth of the way to the Moon. They give a strong radiation dose to anything that passes through them. So much so that they were discovered when Van Allen's instruments refused to give any reading. He thought the radiation detector was broken. Only later, when it was out of the Van Allen belts and started producing readings, did he realise that the opposite had happened – the radiation detector had been driven off-scale by the intense radiation it had encountered!

The Van Allen belts were a source of alarm at the start of the space age – it was even thought that mankind might be permanently trapped on Earth by the invisible cage of their radiation. That worry turns out to be baseless, although mission planners accept that people should not linger in the zones of strongest radiation longer than they need to. Now, we regard the Van Allen belts as a vital part of the zone near the Earth where Earth, Sun and Moon all influence the environment in which most space satellites operate.

The Van Allen belts arise because of the astonishing phenomenon of the solar wind, a never-ceasing blizzard of charged atomic particles, moving at speeds of several hundred kilometres a second, which are thrown out of the Sun as a by-product of its intense heat. It seems that all stars have a solar wind, whose intensity varies with the temperature and type of the star, changing as individual stars evolve. One young, hot type of star, the T Tauri stars, has a particularly strong solar wind. Stars evolve and our Sun once passed through the T Tauri stage, so that an intense solar wind was probably an important factor in the early history of the solar system. The solar wind is now a

much calmer breeze than it once was, but it is still important when we are thinking about the processes which go on between the planets, and in the zones where the solar wind interacts with the magnetic fields of planets. A startling example of this is the aurora, displays of lights in the sky above the arctic (the aurora borealis) and antarctic (the aurora australis). These are caused by especially strong solar wind interacting with the upper atmosphere after being funnelled into the polar regions by the Earth's magnetic field. They are strongest when there have been bright flares on the Sun's surface, which give out very strong bursts of solar radiation. These flares may have an effect on lengthy space journeys – one of the enthusiasts for colonies in space, Gerard O'Neill, has proposed that spacecraft carrying people to the asteroids, a journey of over 100 million kilometres, would need a thick aluminium shelter in which the crew could gather when strong solar flares had been sighted until the particles from it have passed by. The normal flux of the solar wind, and the particles from weak solar flares, could be kept out by a layer of sand or earth.

One of the Earth's oddities is that it has a natural satellite, the Moon. Until the scientific revolution of Kepler and Galileo, everything in the universe was thought to orbit the Earth. Now the field has been whittled down to just one satellite, and one which seems unique in the solar system. For, although every planet except Mercury, Venus and perhaps far-off Pluto seems to have satellites – some planets having them in double figure totals – the Earth's is much nearer to being the equal of the planet it orbits than any other, so that astronomers refer to the Earth – Moon system, in which the two bodies affect each other gravitationally. Since the Earth is only 81 times as heavy as the Moon – no other satellite has anything like 1 per cent the mass of its planet – there is a case for thinking of Earth and Moon as a double planet. The tides are one obvious testament to the Moon's influence upon the Earth, and in some circles there are held to be many others up to and including the onset of lunacy at full moon and the menstrual cycles of women and other female mammals

Any excitement at the Moon's uniqueness in the solar

system and its effects on human life is not backed up by a close look at the Moon itself. No amount of examination six manned missions and many more unmanned ones have allowed a very close look indeed - has given even the inkling of a clue that the Moon is anything but a dead rock. Its atmosphere is very tenuous so much so that there is alarm lest visiting spacecraft disturb it by their emissions. Its magnetic field is weak. There is no strong magnetism generated by turbulent molten metal, as the Earth's core, or a dynamo of liquid hydrogen such as runs Jupiter's high magnetic field. There is no life, or any signs of it like fossils or distinctively biological chemicals. What there is instead is a magnificent laboratory of the history of the solar system, since the craters on the Moon's surface are almost all the result of meteorite impacts in the early stages of the solar system's history. On Earth, geological processes have wiped most of this evidence out, and lunar scientists should be grateful that they can sit in the Earth's comfortable biosphere with a primordial laboratory untouched by human, or any other, hand for billions of years, just 400,000 kilometres away.

The Earth is to be found some 150 million kilometres from the Sun and is the third planet in the solar system. It is also the biggest of the four inner planets – in order, Mercury, Venus, the Earth and Mars – which are all rocky and have only thin atmospheres (thin almost to the point of disappearance in the case of Mercury). Although Mercury, Venus and Mars were all known to ancient astronomers, as were the more distant gas giants Jupiter and Saturn, virtually everything we know about them has been discovered since the start of the space age. The amount which can be found out from telescopes at the base of Earth's turbulent atmosphere is very limited. But during the space age, we have been able to build up a coherent picture of the airless, cratered and small Moon and Mercury, Mars with its thin atmosphere and history of geological activity, and Venus with its dense, acid atmosphere, slow rotation and hot, rocky surface. This zone of the rocky planets is one where, as Freeman Dyson's *Disturbing the Universe* puts it, 'grey' technology will dominate when and if man goes there. These are the planets

where there is lots of sunlight and little water (except on Earth) and where, Dyson thinks, big machinery and the bureaucracies needed to look after them are most likely to flourish, a region of self-reproducing automata of iron, aluminium and silicon, munching rock and drinking sunlight.

Outside this area, we can hope to use what Dyson characterises as 'green' – smaller and more friendly – technology. Beyond Mars we reach the big planets, Jupiter, Saturn, Uranus and Neptune, as well as distant and strange Pluto. Very little is known about Pluto, whose orbit intersects that of Neptune so that it spends part of its 248-year trip round the Sun closer to the Sun than Neptune, nominally the eighth planet. That phase next begins in 1987. Estimates of Pluto's mass and size have been decreasing ever since it was discovered just over 50 years ago. It is possible to draw a graph of the estimates against the time at which they were made and demonstrate that at the present rate, Pluto will disappear entirely this century.

Pluto will not re-enter this story – no spacecraft have been there nor are scheduled to go, and our knowledge of Pluto does not seem to be expanding very rapidly, certainly not fast enough to make up for the apparent shrinkage of the planet itself. The story of the solar system beyond Mars begins, before we reach Jupiter, in an even odder way, with the asteroids.

There are asteroids – pieces of rock ranging in size from the 760 kilometres of Ceres down to a few metres across throughout the solar system, so far as we can tell. Some of them can approach the Earth to within small distances, by astronomical standards. But most of the 2000-plus known asteroids are to be found orbiting between Mars and Jupiter. Astronomy texts, being printed on flat sheets of paper, normally depict them as travelling in a nearly circular, flat, racecourse between the orbits of Mars and Jupiter, but in fact the asteroids are not a text-book illustrator's ideal subject. Many of their orbits are highly elliptical, and many are inclined at steep angles to the Earth's orbit around the Sun, unlike the major planets whose orbits all lie in the same plane, to within a few degrees, and tend to be good approximations to circles,

especially if one leaves Pluto out of the calculations

The asteroids certainly do not total even one per cent of the total mass of the Earth between them. The old thesis that they might represent a planet smashed apart by Jupiter's gravity therefore falls by the wayside, even if it were dynamically possible. The asteroids are, it seems, a remnant of the solar system's earliest days. That means that they are of immense interest to astronomers, who spend much time calculating the shapes of asteroids from their light emissions and attempting to calculate their composition and physical properties, again from their light output. For anybody interested in man in space, they represent a technological opportunity as well as a scientific one. They have been proposed as a natural resource for building space stations – having no great mass, they could be obtained without the fight against gravity which is involved in bringing material from Earth. O'Neill has done some work on tugs to bring the asteroids home. In the longer term, the asteroids may also represent the main resource of living space within the solar system. They could ultimately provide millions of living places where variants of our present trees, animals and plants might be persuaded to live. The same goes for the heads of comets, although as these are periodic visitors to the Sun, spending most of their time at great distances beyond the orbit of Jupiter, the timescale with which they might become a human habitation is much longer. The real opportunity comets present, as the far sighted Dyson has again pointed out, is that they may well occupy the space between the stars in huge numbers and, on that scale, be much the biggest area of potentially habitable space in the galaxy. In addition, the presence of comets between the stars means that the minimum 'jump' through space is a few days' travel at the speed of light, not a few years'.

It seems that most of the comets are to be found in the space between the stars. Comets like Halley's, with a comparatively small orbit, well inside the orbit of Pluto, needing only 76 years to complete, are a rarity. When comets do enter the solar system, what happens to them tends to depend critically on just one factor – whether or not they come close to Jupiter, the biggest planet in the

solar system by more than a factor of three. (Saturn is the nearest competitor.) Jupiter is itself something of a little-league solar system – telescopes and space probes have shown that it has at least 14 satellites, and there are almost certainly others waiting to be discovered. It also has a modest ring of rocky material, less impressive than Saturn's but nonetheless there. And although the centre of Jupiter is much too cool for hydrogen fusion to occur as happens in the Sun (that needs temperatures of billions of degrees), Jupiter produces heat internally, which is rather more important than the Sun's rays in driving the spectacular cloud systems of Jupiter's upper atmosphere. Jupiter is over five times as far from the Sun as the Earth is, so that, area for area, it receives only 4 per cent as much solar energy at the top of its atmosphere as we do.

From the point of view of an imaginary observer on Jupiter, or one of its satellites, the solar system would seem to consist largely of Jupiter itself plus a retinue of satellites, and the giant planets beyond Jupiter. The inner rocky planets would seem unimportant and, depending upon how developed astronomy was, Mercury might be quite hard to see. And only the local science fiction enthusiasts could even envisage life on that hostile third planet, where ice turns to a liquid, and the Sun's rays beat down through a pitifully thin atmosphere. For such an astronomer, Jupiter's own satellites would be a major study – the cracked icy surfaces of Ganymede, Europa and Callisto, for example, with their varying densities of craters to give an idea of the time since they solidified. He would also be able to see the fantastic sulphur volcanoes of Io, the innermost of the four satellites of Jupiter discovered in 1609 by Galileo. Under the influence of tidal forces set up by Jupiter and the large satellites, Io is volcanically active, perhaps more so than any other object in the solar system. The Earth usually has volcanoes only in well-defined areas of geological activity – on Io, it seems from Voyager space observations, volcanoes probably spring up everywhere on the surface from time to time.

Virtually all we know about Jupiter comes from space flybys of the 1970s, although there are plans for other Jupiter probes including a possible Jupiter orbiter in the

1980s. And because spacecraft have not been there yet, apart from one brief Saturn flyby late in 1979, we know a good deal less about the other giant gas planet than we do about Jupiter. That ignorance could be put partly behind us some time this decade. Late in 1980, Saturn with its 10 moons (at least) and its ring system should have been visited by Voyager 1, followed by Voyager 2 in August 1981. If fuel on the Voyagers holds out, Uranus and Neptune are also possible destinations. It seems likely that Saturn, Uranus and Neptune (95, 14 and 17 times as massive as the Earth, respectively) will all turn out to be cooler, less active versions of Jupiter, differing from it in ways which telescopic observations allow us only to guess at. The corner of the universe which these missions is opening up for us is a fascinating one – huge cool, cloudy worlds with fascinating chemistries and large families of gloomy satellites.

The average distance between Neptune and the Sun is 4500 million kilometres. Leaving aside the anomaly of Pluto (and any transplutonian planets waiting to be discovered) that is the outer limit of the solar system, exactly 30 times as far from the Sun as we are here on Earth. Beyond that we find only the comets and a thin scattering of dust, before the stars begin. It takes light about eight minutes to get from the Sun to the Earth, and something over four hours for the trip to Neptune. The nearest star is just over four light years away, about 9000 times as far.

Bold efforts have been made to think through the technologies we shall need if our spacecraft are to make journeys of light years rather than light hours as at present. One of the most startling, called Daedalus, was floated by a group of scientists and engineers belonging to the British Interplanetary Society. Project Daedalus's progenitors cheerfully put in some 10,000 unpaid man hours of expertise to push forward a project which they do not expect to see executed in their lifetimes. Their 192 page report is a model of how to analyse a thoroughly speculative technology. Propulsion, communications, computers, navigation, materials and structures are all looked at, along with the astronomical background to the proposed Daedalus trip.

The final mission selected by the Daedalus planners would involve a 50-year trip to Barnard's Star, the fourth nearest star to the solar system if a nearby double star, proxima and alpha centauri, is counted as two units. (Although the two are physically a double star, locked together in orbit, they are ten thousand times as far apart as the Sun and the Earth.) Why Barnard's Star rather than the nearer Centauri pairs? Because it seems to have planets. Although there are a number of possible ways of accounting for the motion of Barnard's Star through the sky, which is much less smooth than that of other stars, one plausible explanation proposes that it is pulled by the gravity of two planets, one the size of Jupiter and another 0.4 times its size, at distances of 3 and 4 times the distance of the Earth from the Sun, and with orbits of 11 and 22 years. If true, this makes Barnard's Star a very enticing target, although more astronomy would be done to firm up the existence of the planets before a Daedalus-type mission were actually sent there.

The Daedalus project calls for the spacecraft to be assembled near either the Moon or Jupiter and launched from there with its fuel tank full of heavy hydrogen (deuterium) and lighter-than-usual atoms of helium gas. (Jupiter might well be a good source of one or both of these.) The spacecraft would be propelled by the energy produced from fusing these together to yield normal helium and protons. The fusion reaction can only start to happen under very energetic conditions, so that the Daedalus project will only be possible if research now being done on using lasers, electron beams, electromagnetic fields, and other means of getting massive quantities of energy into the area where the fusion is to occur is a success.

By the time a spacecraft sets out for Barnard's Star, however like or unlike Daedalus it looks, the technology for investigating any planets it meets will have developed far beyond the capacity of present planetary probes. Our knowledge of Saturn was enhanced a thousand-fold by a brief flyby in September 1979. With planets light years away, requiring 50-year trips, that simply will not be good enough.

The Daedalus planners point out that it was about 30

years from the British Interplanetary Society's Moon-lander proposal to the first Moon landing in 1969, although it can scarcely be denied that the technology problems with Daedalus are bigger. Nobody is looking to see fusion power stations – which would have a lot in common with the Daedalus propulsion system – this side of say 2025. That is why Daedalus was dreamt up by well-qualified amateurs rather than well-paid professionals at one or another national space agency. But it is these agencies rather than amateur enthusiasts which have so far put people and machines into space; and it is time we took a look at the technology they have devised to allow journeys into space.

The basic tool of space exploration is the rocket. In space there is no air for a propeller to push against – the only way there can be movement is for the motion of a spacecraft in one direction to be balanced by the movement of material in the opposite direction. That sounds tortured, but the principle is one of the most basic in physics. All it involves is the conservation of momentum – rockets work by sending a rapid stream of hot gases out of the back of a spacecraft. the energy with which they leave the craft must be balanced by an equal and opposite push of energy in the opposite direction. That's all there is to it – the spacecraft is pushed forward because the momentum in the whole system has to be constant. There is no action (firing a rocket engine) without an equal and opposite reaction (the rocket being pushed forward). Isaac Newton knew that, and said so in his third law of motion. Knowledge of his laws has been far from universal in the intervening three centuries. The *New York Times*, for example, ran a famous attack in the 1930s on rocket pioneer Robert Goddard – didn't any school-child know that without anything to push against, his rocket couldn't possibly run in space? When a man walked on the Moon, they published a most gracious apology, rather more than thirty years after the harangue had appeared.

Goddard's early experiments were matched by others carried out in the 1930s elsewhere in the world – notably by the Verein für Raumschiffahrt in Germany, of which Werner Von Braun was a leading member at a precociously

early age. But the major impetus to rocket development took place during the Second World War, when rockets of many sizes and uses were developed, including the German V2. The V2 was a massive rocket which used liquid propellant to carry a load of explosive for distances of hundreds of kilometres. The V2 was the big step forward, and later rockets, including both military rockets and rockets used for space research, owe a lot to it in terms of design.

So it is worth noticing that the V2 was, in effect, a programme of unilateral disarmament, carried out by a nation in the depths of war. Every V2 had as much material and expertise in it as an aircraft, but was fired just once, with a warhead equivalent to one small aircraft bomb-load. A worse example of cost-benefit analysis as applied to weaponry could scarcely be imagined, except that it exists. There was also an anti-aircraft rocket, again developed by the Germans, which weighed in at about 60 tonnes, with a warhead of just a few pounds of explosive and it never shot down a single aircraft. The only way the V2 could have been a war winner would have been with a nuclear warhead, and that is one development which the Germans, for many reasons, never came near to managing. After the Second World War, rocket experiments involving German, Soviet and US personnel picked up where the V2 had left off, in the USA and the USSR. In addition to the people who had developed the V2, the end of the war left the temporary allies who had won in possession of many actual V2s plus tonnes of the machine tools and other equipment needed to build them, and plans for even bigger rockets including one which could possibly have hit New York.

The postwar evolution of rockets has been rapid. One recent directory shows that the USA has four rockets available for putting loads into space, or nine if variants on the basic four (Titan, Atlas, Delta and Scout) were counted. The Soviet Union had another four – Soyuz, Proton, SL-12 and SL-13 – and the European Space Agency had one, Ariane There were also four Japanese launchers, Mu3, Mu3H, N-1 and N-2, and the Chinese FB-1. The Titan variants had the biggest declared weight, weighing in at well over 600 tonnes at launch. The biggest version, the

Titan 3C, was capable of putting a 13 tonne load into a 160 km high orbit, or a 1.5 tonne load into a synchronous 24-hour orbit around the Earth. An even smaller load – less than 1.2 tonnes – could be sent clear of the Earth's gravity for interplanetary missions. But Proton, SL-12 and SL-13 could orbit 18 tonnes, send 6.5 tonnes into interplanetary space, and orbit 22 tonnes respectively. (The SL-13 is the rocket used to orbit the Salyut space station.) These rockets are all very large compared to the machines which they are designed to put into space. The total length of the Martin Marietta-built Titan launcher is well over 70 metres, and with the strap-on rockets used at the start of flight, the diameter at the base is nearly 10 metres. The big Soviet launchers are certainly larger. But they are agreed by everyone except their builders to lack the massive technological complexity of the spacecraft they launch.

It was realised early on in rocket technology that the masses of fuel which would be needed to put comparatively small loads into orbit would be prodigious. The question is bound up with 'escape velocity', the velocity which a body must have to escape the Earth's gravity. Earth's escape velocity is just over 40,000 kilometres per hour. For the other planets of the solar system the figure varies from 15,000 kph at Mercury up to 216,000 kph at Jupiter. These massive speeds have to be gained by great accelerations, and that means that huge quantities of fuel have to be expended in the few minutes which the rocket spends accelerating through the Earth's atmosphere.

This leads pretty directly to the main design feature of all space rockets to date: they are all multi-stage rockets. In other words they consist of several rockets used one after the other, plus strap-on booster rockets which can be used in conjunction with the first stage. The first stage is the biggest, carries the most fuel, and has the biggest push. Its function is simple – to give the rest of the spacecraft the shove it needs to get above the atmosphere, after which other stages can do the rest. With the Titan 3C, the first stage plus its boosters provides a 1200 tonne thrust, massively greater than the 45 and 7 tonne thrust of the second and third stages respectively. Each stage is abandoned as it is used, so that the metal carcass of the first

stage need not be carried into orbit. The Titan 3C is the size of a small ship upon launching. Calculations carried out on putting loads into space with one-stage rockets show that something more like an aircraft carrier than the destroyer-sized ensemble which took Americans to the Moon would be needed if it were done that way, since the dead weight of expired rocket would have to be carried all the way instead of being discarded at the end of its useful life.

In principle, a rocket is not a complex device All it needs to do is provide a carefully regulated amount of acceleration. Many rockets, including the massive Titan 3C boosters and all the stages of the small and successful Scout launcher, use solid fuel, which allows an absolute minimum of complexity. Others use liquid fuel, such as hydrogen and oxygen compounds of nitrogen which react explosively when mixed. Liquid fuels are less simple – they have to be pumped, since gravity cannot feed them into the combustion chambers where they are to react anything like fast enough. There are also control problems. The thrust being delivered, by the upper stages especially, has to be controlled accurately to get the spacecraft placed in the correct orbit or, of course, launched into the right interplanetary trajectory. The newest traditional multi-stage, one shot rocket to come into service is called Ariane. It was developed by the European Space Agency, especially the French, as a direct counterweight to the US National Aeronautics and Space Administration's Space Shuttle Ariane is a three-stage rocket standing nearly 40 metres tall upon launch, with a first stage thrust of nearly 160 tonnes. At the time of writing, a great deal of heat was being generated about whether Ariane was going to undercut the Space Shuttle, by offering cheap launch facilities in exactly the way NASA hoped the Shuttle would before its lengthy saga of delays and cost increases started to bite.

Ariane first flew on Christmas Eve 1979, a mere six years after the ESA countries agreed to go ahead with their own launcher. And within days of the first successful launch, Ariane received commercial backing at least as important as the technical demonstration that it could fly American Telephone and Telegraph, one of the biggest forces on US telecommunications, booked a 1983 Ariane launch to orbit

a communications satellite to handle telephone traffic and other communications inside the USA. AT&T already has a booking on the Space Shuttle to launch the same satellite, and presumably plans to take whichever turns out to be the cheaper option. Intelsat, the main international satellite communications operator, plans eventually to use both the Shuttle and Ariane later this decade. Ariane has been billed as the plain Space Agency's riposte to the Space Shuttle juggernaut, so it is worth noting just what a complex device it is. The three stages involve contributions from 66 European corporations, 29 of them from France. Many of them provided electronics, servomotors, computers, controls and gyroscope systems to keep Ariane on its mission schedule. Others provided fuel tanks, pumps and the rocket motors where the combustion of the fuel actually occurs. And there are a host of other engineering necessities like explosive bolts to separate the stages, radio links with the ground, and data collection systems to keep the flight control computers aware of what is happening throughout the spacecraft. That is a lot of complexity within a thin aluminium cylinder four metres wide at the base and even narrower when the upper stages are reached.

The justification for developing Ariane was partly financial. ESA has an impressive launch schedule and did not want to go on paying the Americans to carry it out for them, least of all when it thought it might well be able to do the job cheaper. It was also to do with politics and pride - what price a space agency without rockets? Ariane is a medium-sized rocket, comparable to the USA's Titan or the USSR's Soyuz in size but only able to orbit much smaller loads than either, because of the massive boosters used with Titan and the huge first stage of the Soyuz rocket. The first Ariane launch occurred at almost the same time as the formation of Arianespace, a European commercial launcher organisation with plans to sell Ariane capacity to anyone wanting it. Much of its business will come from European space industries like the Arabsat consortium which aims to provide satellite communications to the Middle East, and which shortly after the first Ariane launch joined AT&T by putting down its $100,000 deposit for a flight. For all the heat and noise created in aerospace

circles by the European challenge to the space shuttle, the fact is that even ESA officials admit that the Shuttle – more formally known as STS, the Space Transportation System – is bound to become a real landmark in man's progress into space. Even if it does not turn out a massive commercial success, and even if the technological problems which now dog it continue when it is in service, the basic idea is right. The STS consists of three main components: two booster rockets, a massive external tank for fuel, and an Orbiter. The plan is simple – to provide a cheap, renewable system for getting loads into orbit.

Even if Ariane and other conventional rockets succeed in retaining the market for small launches of present-day-size communications satellites, for example the STS or something like it will be in the lead when it comes to launching and assembling major structures in space. Its aircraft-sized cargo hold means that the Shuttle will be able to provide the big lifts into orbit which are essential for building large space platforms, although the Shuttle's delays and price rises mean that the cost will be higher than the bargain basement rates quoted when the STS idea was first put forward as a serious project by NASA's Dr George Mueller.

How do the STS's elements add up to give a 'space transportation system'? Re-usability is the essence, and it starts to take effect soon after the Shuttle takes off. The STS leaves the Earth's surface under the power of five engines. Two of these are the Solid Rocket Boosters attached to the external tank. These boosters burn briefly before separating when the Shuttle is 45 kilometres above the ocean. Each SRB is fuelled at launch with 450 tonnes of solid fuel, giving a push of 155 tonnes. After burning out, the SRBs separate from the rest of uhe Shuttle (eight small rockets are incorporated in each SRB to make sure it separates properly), the SRBs parachute to the Earth's surface, to be picked out of the sea, cleaned up, and reused. The 44 metre long SRBs need just two minutes to run through their fuel. After that they would be very expensive scrap metal in any other space launcher.

So far, re-usability has won out. The Shuttle is still accelerating, now under the power only of its three Space

Shuttle Main Engines, the SSMEs. These are powered by fuel drawn from the external tank. (Some heavy loads, thought up mainly by the US Department of Defense, call for an extra booster, again attached to the external tank.) So it is a pity to report that the massive 47 m long, 8 m diameter external tank is not re-usable. The tank consists mainly of two massive compartments – one each for the liquid oxygen and hydrogen which are to be burnt in the SSMEs. The tank is essentially a rocket without a motor. Since engineers cannot find a way of getting the tank back to Earth, they have engineered it to contain as few of the expensive components as possible.

This means that the complexity is mainly to be found in the Shuttle Orbiter itself. The Orbiter can enter a range of orbits around the Earth, but there is a trade-off between the payload which can be put into orbit and the height of the orbit. There is also the option, at a sizeable cost in payload, of bringing the external tank into orbit instead of abandoning it after its fuel is all used up. So we may eventually see communities in space living in gutted 2500 cubic metre external tanks.

The Orbiter is described as being of about the same size as a DC9 aircraft, but a good deal heavier. (Its weight on landing back on Earth should be about 96 tonnes.) The Shuttle will be moving fast when the external tank is jettisoned and falls back to Earth. By then the Orbiter needs only minor adjustments to get into the right orbit. These are provided by the Orbital Manoeuvring System – OMS – engines which are visible at the rear of the Orbiter above the three main engines. The main engines are also adjustable. After the liquid oxygen and hydrogen have ignited to give steam in the combustion chambers, they travel out through nozzles which can swivel on gimbals to adjust the trajectory, as can the SRB motors. The Shuttle's engines can also be controlled later in flight, so that the OMS engines only need add fine tuning. There are two OMS engines, burning liquid fuel, per Orbiter, and with a multi-engined Reaction Control System to allow the Shuttle astronauts to control the Shuttle's attitude in space – whether it is tilted at an angle to its orbit or even travelling round the Earth 'upside down' for particular experiments.

The RCS consists of a total of 44 rockets, and during any one Shuttle mission they will be fired many times. Stripped of its boosters and its main fuel tank, the Orbiter is not a machine of immense power and size. Instead, it is a piece of high technology.

The Orbiter crew should feel pretty much like an aircraft crew for most of their flight – at launch the commander is looking straight upwards, sitting at a bank of controls and instruments which indicate many of the same variables as an aircraft pilot is interested in, such as altitude and the size and direction of the engines' thrust. Most of the action needed to get the Orbiter into the right orbit is taken by the Shuttle's automatic Flight Control System, since things happen quickly and the astronauts are subject to accelerations of up to three times Earth gravity, reducing their effectiveness despite lengthy training

Once in orbit, the shuttle crew leave the aircraft-style flight deck to start carrying out their missions in space, which can last from a week to a month. The STS launch schedule is subject to constant revision, but one current in February 1980 showed that there were to be 39 flights between 1980 or 1981, the first proving flight, and 1984. Some of these are 'opportunity flights', and the betting is that a fair fraction of these so far undetailed opportunities of getting payloads into space will be taken up by the Department of Defense or other bodies in roughly the same line of business.

The other missions involve a wide range of space activities, allowing us a look at the full potential of the space shuttle. Many of the missions involve launching satellites, including communications satellites (national and international, commercial and military), and others like weather and remote sensing satellites. There are also scientific payloads like the space telescope and possibly the Galileo Jupiter probe. And there are satellite retrievals. Some of these are intended to bring satellites back to Earth when they have finished their tasks, like the Solar Maximum Mission now due to be recovered from space early in 1982. As time goes on, there will also possibly be a case for repairing satellites in space rather than replacing them, to avoid the need to launch a replacement expens-

ively from the Earth's surface.

Satellite launches and retrievals account for the vast bulk of the planned STS trips, which are to be carried out by three STS ensembles based at Kennedy Space Center on the US Atlantic Coast and Vandenberg Air Force Base on the Pacific Coast. If these launches are not profitable, the Shuttle will be a very costly failure. But the Orbiter cannot put a satellite into orbit as easily as opening a window and hurling it out. There have already been tests of machinery designed to inject satellites into desired orbits from the Shuttle. When the Shuttle is fully in use, the distinction between manned and unmanned space missions will alter – every launch carried out with the Shuttle will involve astronauts.

The 'robot arm' is the main satellite-launching machine which is needed to supplement the Shuttle. At the time of writing, the arm had been extensively tested on the ground and, since it owes a lot to tried and tested robots working in earthly locations from nuclear fuel plants to car factories, it seems likely to work reasonably as predicted. The arm is known to acronym fanciers – who are many among Shuttle executives – as the RMS, for Remote Manipulator System. It consists of a triple-jointed arm nearly 15 metres long and strong enough to heave loads of several tonnes, as big as the largest satellites and other loads which the Shuttle is likely to have to handle. While it is operating, the Shuttle astronauts will control it via a TV link from their air conditioned control cabin, a far cry from the complex and potentially dangerous space walks which have so far been an essential part of the manned space programme. There is also a small 'yoke mounting' which can be used to put smaller loads into orbit.

Not every load which the STS is intended to launch will be put directly into orbit by the Shuttle, which can enter only orbits low above the Earth's atmosphere. Many satellites are placed into orbit in these regions, but there are many useful satellite orbits which cannot be reached directly with the Shuttle, the most important being so-called geostationary orbits some 36,000 kilometres above the Earth's surface. These are especially important for communications satellites, and our chapter on satellite

communications shows how the idea was first put forward in a pioneering paper on space communications. But first, some background on orbits.

Astronomers have accepted for thousands of years that the Moon's motion among the stars of the night sky could best be explained by assuming that the Moon travels in an almost circular orbit about the Earth. Some ancient races, it seems from the remains of their observatories, went much further and became genuinely expert in analysing the positions of celestial objects, including the wrinkles of the Moon's orbit. With the planets, which we now know orbit the Sun, things are more complex. In the West, explanations of their motion based on orbits around the Earth were prevalent until the seventeenth century, when it became generally accepted that the planets orbit the Earth. Satellites of other planets began to be discovered at the same time, beginning with Io, Europa, Ganymede and Callisto, the four biggest satellites of Jupiter, which were discovered by Galileo, on one of the first occasions on which a telescope was turned on the sky.

Equally importantly for the space age, seventeenth-century scientists came up for the first time with some reasons why astronomical objects thousands, millions or even billions of kilometres apart, should do such an odd thing as moving about each other in more or less irregular elliptical pathways. The answer, of course, has to do with gravity, and even more to do with the 'universal law of gravitation' formulated by Isaac Newton in 1666. It was the year of the great plague in England; Cambridge University, where he should have been, was closed to avoid the infection and he was working at his mother's house. He showed that the Moon's movement around the Earth could be explained by a force between objects which increased directly as they became more massive and decreased as they became further apart; not directly, this time, but according to the square of the distance.

On this basis, Newton calculated what force would be needed to keep the Moon in its orbit, rather as if it were a ball thrown up with such speed that it did not fall back to Earth. Instead, its motion balances the force with which the Earth was trying to pull it down. The calculations worked.

The force needed to keep the Moon in its orbit was what Newton expected from the strength of the gravitational pull, on an apple or anything else, at the Earth's surface. As Jacob Bronowski said in *The Ascent of Man*, 'When the figures come out right like that, you know as Pythagoras did that a secret of nature is open in the palm of your hand. A universal law governs the majestic clockwork of the heavens, in which the motion of the Moon is one harmonious incident.' Later on, Newton did the same calculations for the then known planets of the solar system – again they worked, and they go on doing so.

Now the satellites which rockets, or even the space shuttle, put into orbit are just miniature Moons. Their orbits are governed by laws of planetary motion set out by Kepler in the seventeenth century and later explained by Newton's gravity. There are just three of Kepler's laws: one says that planetary orbits are elliptical, with the Sun at one focus of the ellipse, and the same goes for satellite orbits including artificial satellite orbits around the Earth. The second says that a line between a planet and the Sun (or a satellite and the Earth) will sweep out equal areas in equal times. So if the ellipse is highly irregular, the satellite will move much faster when it is near the Earth than it will in deep space. The most striking examples of this in the natural solar system are comets. Most of these spend most of their time moving languidly in deep space, far from the Sun, but when they sweep close by the Sun they do so at massive speeds. The third law says that a planet or a satellite's orbital period is related to its average distance from the object it orbits. The relationship is complex – the square of the time is proportional to the cube of the average distance.

These rules have all sorts of interesting astronomical consequences, but they also allow us to think about satellite orbits. It would have been obvious to Newton that at some average height above the Earth, a satellite, natural or artificial, is going to have an orbital period of just 24 hours, the time which the Earth takes to rotate once on its axis. There are an infinite number of such orbits – the only rule is that the Earth must be at one focus of the ellipse, and the average distance from the Earth's surface must be some

35,000 kilometres. But if the orbit is nearly circular, and is in the plane of the Earth's equator, so that the satellite moves round at the same rate as the Earth's rotation and, of course, in the same direction, another effect appears - the satellite appears to hang stationary in the sky from the point of view of any observer on Earth who can see it, since satellite and ground have matching rotations.

This means that even small antennae can be used to communicate with satellites in geostationary orbits – there is no need to track the satellite, and it is always in view. So many satellites, especially for communications, are placed in geostationary orbits and there is an increasing problem of scarcity of geostationary space, especially, for example, over the Atlantic because of the rapid growth in telecommunications traffic there.

Geostationary satellites are a growing trend (the Russians are now taking them seriously, as explained below) but not every satellite application is best served that way. Thus Soviet communications satellites have so far typically been placed into orbits with a high inclination to the Earth's equator, so that they spend most of their time over the Soviet Union. A series of them spaced at intervals around the same orbit allows continuous coverage of the USSR, although the Soviets now seem to think that even high latitudes in the USSR can be served well by geostationary satellites. Other uses which demand satellites in orbits with a high inclination to the equator include Earth surveillance. The successful US Landsat satellites have so far been placed in Sun-sychronous orbits inclined to the equator. These orbits are inclined to the equator, and the satellite sweeps out a path over the Earth every few days, allowing the vast majority of its surface to be observed. The trick is that the satellite's orbit is tied to the Earth's rotation, so that it is always the same time (in fact 0930 hours) below the Landsat as it orbits the Earth. So the pictures are all taken in the same lighting conditions and may be directly compared.

So there are wide choices for useful orbits in which satellites can be placed, and there are also problems for the people who have to get them into orbit. The space Shuttle, even armed with its yoke and robot arm to hurl satellites

into orbit, cannot manage to get every satellite it must launch into the right orbit unaided. The US Department of Defense was especially exercised about this problem during the early stages of Shuttle development, and was the prime mover behind developing the Inertial Upper Stage, a US Air Force NASA solid-fueled two stage rocket built by Boeing in the form of a stubby 5 metre long, 3 metre diameter cylinder. Being designed exclusively for operations outside the Earth's atmosphere, IUS concedes nothing to streamlining, which is a major design consideration for Earth-launched rockets. The IUS seemed, early in 1980, to be suffering from the same technology and budget problems as the Shuttle itself – time and money were both being ripped through in a way which neither NASA nor the Air Force originally planned, although (again like the Shuttle) there seemed to be few doubts that IUS would fly, albeit later and more expensively than originally planned. At that time, there was such a question mark over the space Shuttle IUS combination that an investigation was being mounted to see whether the pair would have the performance needed to put their first load, the Tracking and Data Relay Satellite, into orbit. Among the options being contemplated to save weight were using a lightweight external tank (although such a tank was under development, waiting for it to become available would mean a further wait), adding more booster power to the Shuttle, or even giving the satellite less of the propellant it needs for altering its own orbit, thereby presumably shortening its life.

There are other options for putting Shuttle loads into high orbits, including one existing upper stage, Centaur. There is also to be a Solid Spinning Upper Stage with the capacity to lift two and a half tonne payloads from the Shuttle to geostationary orbits, or one and a half tonne loads out of the Earth's gravity for interplanetary missions.

Budgetary and technology problems with IUS do not affect only the US Air Force, since IUS should also be available to launch civilian loads including interplanetary missions like the two-part Galileo Jupiter probe. But Earth-orbiting scientific experiments have their own Space Shuttle facility, called Spacelab, developed by a European

consortium, led by West Germany. Spacelab is designed to fit in the Shuttle Orbiter's cargo hold and have, like the Shuttle itself, a manned pressurised part providing a working environment where space suits are unnecessary, and an unpressurised area, open to space, for carrying out observations of the Earth or astronomical objects. As a European Space Agency handout enthuses, 'Spacelab's skies will be cloudless'.

Hundreds of experiments are due to be flown in Spacelab missions using two almost identical Spacelabs – in the early 1980s, and a European crew of scientists is being trained to carry them out. They will run experiments on the unpressurised pallets as well as on a gravity-free work-bench inside the lab, where biology, materials processing, and other science will be possible. There is also the prospect, according to a British study which reported early in 1980, of using the Spacelab pallets as free-floating experimental platforms, with the addition of some extra equipment, or even as the basic unit of a space station which might be built up out of a number of pallets.

The Space Transportation System, therefore, is a well thought through means of accomplishing complex tasks in space. Just how complex some of them might be will become apparent later, in discussions of the big permanent space stations which the STS may make possible. Of course, there is just one other problem for the Shuttle – getting back home with the Orbiter in a fit state to fly again. To do this, the Orbiter has to re-enter the Earth's atmosphere and land safely. The first part of the problem depends on good insulation, to soak up the massive amounts of heat produced in the Orbiter's flight into the upper atmosphere. The device chosen to achieve that insulation was simple enough in conception – thousands of small tiles, of a highly heat-absorbing material. The problem came later, as the first attempts were made to get the tiles firmly on to Columbia, the first Orbiter. The task turned out massively more complex than anyone had foreseen (apart from a few mavericks who had been ignored) and the tiles soon became one of the most massive factors in the years of delay before the first Shuttle launch. The tiles should last the whole of the 100-mission life

required of the Orbiters instead fears grew in 1979 and 1980 that a number of the tiles might be lost on the first launch, so that a contract was let for a repair kit to enable a space-walking astronaut to go round the Orbiter replacing missing or suspect tiles. Early in 1980, the tiles were still being tested on high-flying aircraft, and new ideas about their being used as load-bearing components as well as for insulation were coming forward, showing that the basic problem of Shuttle thermal insulation was not thoroughly solved even in principle. The Shuttle tile affair is big technology at its worst. The basic idea - well over 30,000 tiles per Orbiter, each a few centimetres square, all precisely shaped to the Orbiter's own outside geometry so that fitting them was bound to be a highly skilled task – was bound to lead to problems, and it did. Even in 1980, less than a year before what was then the Shuttle's scheduled first launch date, problems were arising about testing the tiles – it seemed that many of them would have to be removed for testing and then glued back, and the same procedure might have to be repeated for at least some of the tiles between each Shuttle flight once the STS programme is fully under way. Existing plans involve turn-round times of about a week for the Shuttle, which allows for maintenance but not for major testing of thousands of vital insulation tiles

This is the sort of problem which could make the Shuttle programme, ostensibly simple, re usable space technology at a high level of development, disintegrate into slow, costly space technology, with crippling effects on future space developments That applies especially if Shuttle astronauts have got to consult cameras surrounding the Orbiter while in space to look for faulty tiles and then leave the Orbiter to repair them, since space walks are just the kind of complex procedure which the Shuttle was first meant to avoid. The astronauts may even have to carry out the examination by space walking. The main beneficiaries seem likely to be Martin Marietta, recipient of the $2.1 million design and development contract for the Shuttle tile repair kit. Assuming the tile problem is overcome, the last part of any Shuttle mission ought to be the easiest. The Orbiter simply re enters into the atmosphere, almost like a traditional space capsule and lands, on a salt flat or even a man-made

runway, for all the world like a conventional aircraft. Put that way, it seems simple enough. But the re-entry (especially because of the doubt about the tiles) is a key part of the reason why a group of three ex-astronauts said before the first Shuttle launch that STS missions were likely to be less safe than the earlier US manned spaceflights. (They blamed inadequate financial and political backing.) Although the Orbiter can fly like an aircraft, it has to be landed without power, potentially a problem.

Despite these reservations, the space Shuttle idea is not unique to the US space effort. In 1978, the Russians test flew a re-usable aircraft-type rocket plane from an aircraft, an experiment strongly resembling the test flight of *Enterprise*, the Shuttle Orbiter prototype, from a jumbo jet. The fact that the Russians are allowing some facts to drift out about their rocket plane indicates that they are confident of success, perhaps even before the Shuttle has got into its stride. With all the bad publicity due to the Shuttle delays, the NASA engineers must be relieved that if a mistake has been made with the STS, the Russians are making it too.

Even if the Shuttle is a lot less economical than the first plane showed it ought to be, a reasonable level of business ought to be assured by the US Air Force. As David Baker pointed out in the British magazine *Flight International*, the Shuttle's size – giving it an ability to put a 29.5 tonne payload into a low orbit launched eastwards (so that the Earth's rotation helps it on its way) – was largely dictated by the USAF. The Air Force wants to launch big satellites and now speaks of space as just another operational area. NASA would have gone for something smaller, but needed the Pentagon's political backing. But NASA planners, too, see the need for a big Shuttle in the long term, to launch the components of big orbital space platforms. So it is studying options for getting even bigger loads into space, including liquid-fuel boosters for the existing STS arrangement (mainly for USAF payloads at present), using an unmanned freight carrier instead of the Orbiter, or using more Solid Rocket Boosters than the two envisaged in the present Shuttle plans. Some schemes now on the drawing board could mean lifting payloads of up to 450 tonnes into

low orbits, although studies of loads beyond 300 tonnes are only in outline at the moment.

There are also studies under way of single stage re-usable spacecraft, aircraft-like vehicles which could make the round trip to space and back. One Boeing scheme would use a rocket-assisted sled to get the plane moving at the high speeds required. The main client could again well be the USAF, since the single-stage space vehicles would be

WORLD LAUNCHERS: HOW MANY TONNES INTO ORBIT?

Mission	*Low circular orbit*	*Geosynchronous orbit*
Shuttle, USA	30	variable
Delta/USA	2.5	0.9
Atlas-Centaur/ USA	6.5	1.9
Ariane-1/Europe	4.5	1.7
Soyuz/USSR	7.5	2.4
Zond USSR	22	5
Titan 3C/USA	15	4.5

Source: ESA

able to make a much faster takeoff into space than the existing STS arrangement. These vehicles could have a life of up to 1000 missions, not the 100 planned for the STS and now threatened by the tile problem. (New insulating materials are also under development for the Shuttle's successors.)

Space launchers, however complicated, are of course just a means to an end – the end being to get spacecraft, manned or unmanned, off the Earth's surface and away from the Earth's gravity. If the Shuttle works out, there will be more and more call for rockets like the Inertial Upper Stage, designed to carry loads about in free space. But it is important to realise that spacecraft themselves have changed drastically since the space age began. Any spacecraft consists of several basic elements – a power supply, a communications set-up, control systems, life support systems if it has people or animals on board, and of course the equipment needed for whatever mission it has to

carry out. In addition, there may be one or more small rockets on board for altering the orbit of the satellite or for changes of course deep in space with an interplanetary mission.

Since the start of the space age, there have been dramatic advances in each of these spacecraft elements, and spacecraft themselves have grown larger and more complex. Increased size means increased power. According to British Aerospace, the biggest fabricator outside the USA and the USSR of the silicon arrays used to generate electricity in space, the power requirements of satellites have been growing by a power of ten every decade since the

SIZES OF MAJOR MANNED SPACECRAFT

	Mass in orbit tonnes	*Length m*	*Maximum diameter m*
Space Shuttle Orbiter	69	37	24
Spacelab	14.5	11	4.2
Skylab	90	36	6.58
Salyut 6		about 12	4.15

space age began. (The same British Aerospace publication also refers, unforgettably, to the 'Space Shuffle'.) The same rate of growth is expected to continue into the future. The electric power used by communications satellites, for instance, has built up from the 40 Watts of Intelsat I in 1965 to 1200 Watts for the Intelsat V communications satellites now in use. And Echo, in 1960 the first communications satellite launched, was just a metal-coated reflecting balloon in space, using no power at all.

So in just over 15 years, communications satellites have gone from using the power of a dim light bulb to the power of an electric fire. The electricity is generated by allowing sunlight to strip electrons off atoms of silicon, a semiconducting element with properties partway between a metal and a non-metal. Weight considerations do not make it feasible to carry batteries into space for most applications, least of all with all that free sunlight available. This means that spacecraft builders have learnt the art of fabricating large arrays of silicon, a skill which may prove

to have significant applications back on Earth. By the end of the century, spacecraft could be using up to 1000 times as much power as the Intelsat Vs now do, and dramatically more if schemes to build solar power satellites in space, designed to beam microwave power down to Earth, come to anything.

In addition to learning about large silicon arrays, spacecraft makers have had to find out about small nuclear power reactors, mainly for military satellites where silicon collectors might be vulnerable, for deep space missions to outer parts of the solar system where there is not enough sun power available to make silicon a useful option, and for use on the Moon where the Sun is unavailable half the time.

The other area of spacecraft design which has made massive progress in recent years is control and automation. Early spacecraft had to be controlled from the ground to a much greater extent than modern ones do. There are two main reasons for the change. The first is simply that computer power has got cheaper and lighter, allowing more logic to be carried into space at a lower cost. (Machines are also cheaper than technicians.) The other factor is that deep space missions need internal control – they are hours away at the speed of light, so that they simply cannot be controlled from Earth during crucial periods like planetary flybys.

Cleverer and more powerful spacecraft will almost certainly come to be space-going robots in all but name. Dr Ewal Heer of NASA's Jet Propulsion Laboratory said in a 1979 article in *Robotics Age* that the main requirement which still has to be met for this to become a reality is vision, to locate and identify objects in space near the spacecraft, especially if robots are to be used in space construction projects. There will, he thinks, be great advantages for astronauts, who can look forward to having their capabilities in space enhanced by automated joining tools, torque wrenches, and so on.

The missions which these larger, cleverer satellites will carry out are the main theme of this book. Using sensors already in existence or being developed, they can do everything from giving us scattered clues about the origin of the universe to filling the Earth's airwaves with the most

THE PLANETS

	Distance to sun (millions kilometres)	*Diameter (thousands of kms)*	*Mass (Earth = 1)*	*Satellites*	*Escape velocity (km per sec)*	*Solid surface temperature (° C)*	*Solar input (per unit area: Earth = 1)*
Mercury	58	5	0 06	0	4	100-650	6.7
Venus	108	12	0 81	0	10	740	1 9
Earth	150	13	1	1	11	230-320	1
(Moon)	150						
(to Earth	0.4)	4	0 01	—	2	100-400	1
Mars	228	7	0 1	2	5	150 300	0 43
Jupiter	778	140	318	14 +	60	—	0 034
Saturn	1430	120	95	10 +	40	—	0.01
Uranus	2870	52	15	5	20	-	0.0003
Neptune	4500	50	17	2	25	—	0.0001
Pluto	5900	6?	0 1?	1	?	?	0.00006

insulting programming that television networks can think up. One of the things this book will not describe are the measures being taken to bring space activities under strong political control, for the general good of the world's people.

The reason these measures are not described is that nobody is taking them. It is important that they begin to be taken, and that they make more rapid progress than the (in many ways analogous) international discussions taking place perennially on the law of the sea. The promise of space is vast, and it will be a disaster if it is exploited, as both space and the oceans have been so far, simply by the nations with the money and technology to do so.

2 Man in Space

The idea of man in space is a new one. In Western culture, and other cultures around the world, the idea of flight is ancient, although the reality only began in the last two centuries with the first hydrogen balloon flight in 1783. Early notions of flying were distinctly ill-informed. Even if Daedalus had been able to use his own muscles to fly, he would have frozen to death at a great height instead of falling to death after the wax holding his wings in place melted. In the twentieth century, the pace of developments in atmospheric and space flight – often crammed together into a highly mixed bag called Aerospace – has become hectic. The first manned spaceflight was in 1961, less than 60 years after the first powered flight in the atmosphere.

Powered aircraft are generally held to have begun with the Wright brothers in the USA in 1903, but it is appropriate that the first astronaut was a Russian, Yuri Gagarin. Manned spaceflight as we understand it was substantially the brainchild of a Russian. He was born in 1857 – the launch of the USSR's Sputnik I was timed, it is thought, to coincide with his birthdate – and lived until 1935. His name is normally rendered in English as Konstantin Eduardovich Tsiolovsky. It was he who sowed the intellectual seeds of a possible space programme in the Kremlin, long before the German rocket researchers of the 1930s and 1940s made the idea a real possibility. And unlike earlier science fiction accounts of man in space Tsiolovsky's makes use of technology which we would recognise today. Some earlier fictional space voyages, like Kepler's *Somnium* are vague about the technology (*Somnium* is set in a dream). Others, like Jules Verne's *First Men in the Moon* and *From the Earth to the Moon*, contain fairly fundamental errors. Thus in Verne's account – and H. G. Wells's Martian invasion of Earth described in *War*

of the Worlds – the spacecraft are launched not by multi-stage rockets, accelerating them gently until they build up speed to escape from the Earth's gravity, but from big guns. Such a massive cannon would administer all the acceleration at once, making the projectile melt because of atmospheric friction and killing anyone inside by the force of the initial acceleration. Tsiolovsky thought out problems of that kind – although he did not experiment with rockets like his successor in the USA, Robert Goddard. So the Russian cosmonauts are Tsiolovsky's intellectual successors, and it is only fair that one of the biggest and best craters on the Moon's far side, first seen by a Soviet spacecraft, is named after him.

By the early 1980s, Soviet manned spaceflight has run through several stages of development from simple one-man spacecraft to manned space stations. It has also involved the first and only woman in space and – in a move which will be followed up by flights of European astronauts on Soviet and US space flights in the 1980s – flights by East European cosmonauts. How has Soviet manned spaceflight developed? The USSR's manned space programme began with Gagarin and Vostok 1, the first of six one-cosmonaut Vostok flights. The sixth carried Valentina Terschova, so far the only woman cosmonaut. (A number of women astronauts are in training in the USA and are expected to fly in the early 1980s.) The Vostok spaceflights, like the early US Mercury ones, required little skill on the part of the retrained fighter pilots who manned them. These are only just being eased out of manned spaceflight by scientists, doctors and others. The Vostok and Mercury flights were indeed capable of flying unmanned. They consisted of little more than a simple heat-shielded manned capsule launched by a missile designed for military use. The Vostok capsule re-entered the atmosphere after a downward push from a small rocket and – like subsequent Soviet re-entries – landed on solid ground, in contrast to the ritual US splashdowns, now due to be made redundant by aircraft-type Shuttle landings. Althought Vostok now seems almost as remote as the Wrights' at Kitty Hawk, it contained the seed of Soviet space developments which are now starting to flower. Vostoks 3 and 4, in August 1962,

and 5 and 6 in June 1963, were joint operations involving pairs of manned spacecraft in orbit at the same time, sometimes within a few kilometres of each other. These flights were the precursors of later Soviet space link-ups designed to lead to large permanent manned space stations.

After Vostok came a curious interregnum in Soviet manned flight, with two Voskhod flights. The Voskhod craft – the first flew in October 1964 and the second in March 1965 – could carry three men each. Reginald Turnill, in his useful book *Manned Spaceflight*, suggests that the motivation for the Voskhod flights may have been simply the desire to put three Soviet men in orbit before the 2-man Gemini spaceflights were begun by the USA. The Voskhod vehicle and launcher seems to have been little more than a beefed-up Vostok. Turnill adds that a telephone conversation between Nikolai Kruschev, the then Soviet prime minister, and the Voskhod 1 astronauts was Kruschev's last public statement. While making it he observed that the Soviet head of state, Mikoyan, was pulling the microphone from his hand. The next day he was ousted. The Voskhod 1 flight was also remarkable for carrying the first non-pilot into space. He was Dr Boris Yegerov, a physician. Another step forward was on the Voskhod 2 flight – which used only two cosmonauts when one of them, a space-suited Alexei Leonov, made the first 'walk' in space, lasting about 10 minutes. Space walking, usually known by the rather less attractive American term EVA - extra-vehicular activity – is obviously an essential part of the experience needed to carry out full-scale engineering in space, although with time it may well become possible to use robots rather than people to carry out work in space.

After Voskhod began the Soyuz series of Soviet space missions which is still continuing – Soyuz 33 was the last flight of 1979, and more Soyuz flights are expected in the 1980s. Soyuz 37 had been reached by the end of 1980. The Soyuz flights have involved space link-ups which have constituted the first genuine space colonies, inhabited by their crews for lengthy periods of time and replenished from Earth by supply rockets. The most successful of these was Salyut 6, which was launched without a crew in 1977. It

was in use, visited by seven crews, between then and late 1979 and in 1980 was visited by five crews of cosmonauts. But neither the Salyut nor the Soyuz programmes had been trouble-free between 1967 and the end of the 1970s.

Soyuz 1 was, by any standard, a bad start to the series. Although its lone cosmonaut, Vladimir Komarov, stayed in space for just over a day, making 18 orbits of the Earth, he was killed on touchdown by a failure in his parachute system. Soyuz 2 was an unmanned flight, which made a simulated rendezvous with Soyuz 3, with a single crew member. A few months later, in January 1969, came the first genuine Soyuz docking, between Soyuz 4 and 5. One man went up in Soyuz 4 and three in Soyuz 5, for the return trip the numbers were reversed. That October a triple link-up of Soyuz 6, 7 and 8 was carried out.

The Salyut space station series began in 1971, with the Salyut 1 station. This was visited by the Soyuz 10 crew, which did not enter it, and the Soyuz 11 one, which did. But in June 1971, after just over three weeks in the Salyut space station, the three man Soyuz 11 crew were all killed, again upon re-entry. Salyut 2 and Cosmos 557, an unannounced Salyut station, were both failures. Salyut 3 was launched cleanly in mid-1974. But the second Soyuz crew to attempt docking with Salyut 3, Soyuz 15, had problems and made an enforced return to Earth. There was more luck with Salyut 4 – the Soyuz 17 crew stayed on board it for nearly a month – but between Soyuz 17 and 18 was another debacle, an unnumbered flight which was aborted without even reaching orbit, something which has never happened to a manned US spaceflight and which even Soviet information officials were unable to paint as a victory.

Soyuz 19 in July 1975 will be remembered in the history books as the Soviet half of the first joint US-Soviet space mission, docking for two days with a US Apollo spacecraft. The original plan was for both craft to dock with a Salyut station, but in the end a connecting tube was used, instead, to allow the two spacecraft to be mated together. As a contribution to manned spaceflight ASTP, as the Apollo-Soyuz programme was called, was not great. There are few signs of its coming to much in terms of collaboration on

further US-Soviet space projects or indeed co-operation back on Earth. Despite one emergency return to Earth, involving another involuntary first for the Soviets, a splashdown in Lake Tengiz in Kazakhstan, by the crew of Soyuz 23, the Soyuz-Salyut campaign proceeded comparatively smoothly after ASTP to Salyut 6, launched in September 1977. This became the Soviet Union's biggest manned space triumph, shattering all previous endurance records for manned spaceflight.

Salyut 6 is a highly developed space station. Unlike previous Salyuts it is able, for instance, to receive two spacecraft at once. It has two docking ports. Two crews can occupy it at once, or it can be replenished by a 'Progress' supply rocket at one port, with a Soyuz capsule already docked to the other. Salyut 6 is, in effect, the major part of a two-part space station, since when it is occupied there is always a Soyuz spacecraft docked with it. The total volume for crew is about 90 cubic metres – 100 if the Soyuz is counted in – which is not generous when, as has happened, there are four people on board. It is 15 metres long and weighs 19 tonnes. With a spacecraft docked at each of its ports the length goes up to 30 metres and the weight to 32 tonnes.

The space station itself consists of three sections, each narrower than the one before, with the widest nearest the ground when the station was launched. The widest section is 4.1 m wide and about as long. The small section is 3.8 m long and 3 m in diameter; the two are joined by the third section, a 1.2 m long cone. There is a facility for docking a spacecraft at either end, but in practice the Progress supply ships have to be docked at the fat end, since only there can fuel be transferred to the Salyut station. The other main external feature is a set of three solar panels, nearly as long as the spacecraft itself. There are also a number of antennas for communications with the Earth and with other spacecraft. Salyut 6 is both a science laboratory and a place to live. Because cosmonauts on board Salyut stations have to spend months in isolation from almost everything – from gravity to human companionship – which the Earth can offer, Salyut 6 has a large medical section, involving exercise equipment like a training machine, and plenty to

keep the cosmonauts distracted, including books, music, and TV and telex links to the ground. The exercise seems to have been effective, the last group of cosmonauts to have left Salyut 6 at the time of writing Leonid Popov and Valery Ryumin seemed in good condition after 185 days in space. They simulated at least part of the effect of gravity by wearing vacuum suits to apply suction to the bottom half of their bodies.

In total, four main two-man crews visited Salyut 6 between 1977 and 1980, despite the failure of the first attempt to reach the craft, made by Soyuz 25 in October 1977. While there, the main crews were visited by eleven other Soyuz spacecraft, including those used for returning crews to earth. The last eight visiting crews each involved one Soviet crew member and another from a second Comecon country –Czechoslovakia, Poland, East Germany, Cuba, Vietnam and Bulgaria were thus brought in on the act.

The Salyut cosmonauts have had a busy agenda apart from housekeeping activities, keeping in touch with the Earth, exercising and sleeping, they have had to carry out experiments in several key areas to do with the future of manned space stations These come in several categories, including experiments to see what scientific research can be done by man in space, and technology experiments on possible space processes The science experiments have been wide-ranging –one involving a fold-out radio telescope is described in this book's chapter on science in space. The telescope was brought from Earth by Progress 7 and used after being manoeuvred out of the Progress docking port, and unfolded. When the cosmonauts wished to return to Earth, Ryumin made a space walk to release the telescope so that the port could be used again. Another science experiment was the celebrated attempt to grow tulips in space This seems to have ended in failure, possibly because of the lack of gravity which may inhibit the plants' ability to dispose of waste products. The tulips were willing enough to grow, but did not bloom. Other experiments worked out better some Salyut 6 wheat germinated, for instance, and some space-grown spring onions were eaten.

Other experiments carried out on board Salyut 6

involved materials science, and especially the prospect of growing very large and pure crystals in space. This would allow large electronic microprocessors to be fabricated, and so allow more sophisticated electronic equipment to be built. At the moment imperfections in crystals of silicon and other semi-conductors are a major limiting factor on microelectronics, forcing scientists to look for ever more delicate ways of using the small areas of flawless silicon which can form under Earth gravity. The Salyut experiments seemingly showed that large crystals of compounds like gallium arsenide and indium antimonide can be grown successfully in space. There were also experiments in melting super-pure glass for optical purposes and, according to the Soviets, space-melted glass and crystals are already in use in some terrestrial applications And there were experiments on applying metal coatings by evaporation – important for electronics manufacture and fabricating optical telescopes. Other scientific work carried out on board Salyut 6 had to do with remote sensing – plankton-rich fish pastures, geological faults, and crop yields are among the things which were overtly observed. Salyuts 3 and 5 seem to have carried out a disproportionate amount of military work, but it is a good bet that Salyut 6 also made less well publicised observations of the Earth's surface.

But the experiments carried out on Salyut 6 with the biggest long term potential may well be those on man in space. There were initial reports after Lyakhov and Ryumin returned to Earth that they had trouble standing up and even holding a bunch of flowers (just as well the tulips didn't bloom) but the ill effects seem to have worn off rapidly. According to Academician Oleg Gazenko, Director of the USSR's Institute of Medical and Biological Problems, the changes which affected Lyakhov and Ryumin 'were mostly of an adaptive nature and, to a lesser extent, structural There are no reasons to classify them as impairing.' But there is a problem, which is that although men can adapt to space without too many problems, the return to the Earth can be difficult if they have been out of gravity for a long time. As Gazenko says, the potential of space is great but biology is conservative: in the short term, he appears (from an imperfect translation of his thinking

on the matter) to think that the problem will be solved by looking for genetic and other characteristics which characterise people who are specially resistant to space conditions. In the long term, according to Gazenko, people in space will have more mutations than we do on Earth because there is more radiation there to alter their genes. But the mutations will be random and will not produce a 'space man' more suited to life in space except over a very long period.

Although the use of non-Soviet astronauts on Salyut 6 missions was a propaganda first for the USSR, beating the intended European astronaut journeys on the space Shuttle by a number of years, it seems that Salyut's use of robots, the most advanced yet seen in orbit, was a bigger technological first. The Salyut achievements were made possible by a mixture of people and machinery which seems to have been more sophisticated than anything before used in space except, possibly, during the Soviet lunar rover trips, made under the guidance of a control crew back on Earth. The most startling example of the use of robots was the series of eleven Progress transport rockets used to replenish the station. These, like Salyut and Soyuz, were put into space by the large Soviet Proton rocket, which seems to be capable of lifting a load of about 20 tonnes into orbit. It seems that the Progress capsule is essentially a modified Salyut craft altered to carry freight. The docking and undocking of the Progress craft is carried out as a joint operation between ground control in the USSR and the cosmonauts, although the cosmonauts themselves do the final docking once the Progress craft has been brought close enough to the station. Each Progress craft can carry about 2.5 tonnes of fuel and other equipment to the spacecraft. On the Salyut 6 mission, nothing was allowed to go to waste. The cosmonauts filled each Progress craft with what are termed waste liquids before releasing it to burn out over the Pacific.

Life on board Salyut 6 seems to have been little preferable to other space missions such as the Apollo Moon trips, with, for example, a diet largely of courses which could be swallowed in one bite, to prevent crumbs running amok in the weightless atmosphere. That sort of

problem will keep on recurring in space exploration until large space stations are built which can spin to produce a semblance of Earth gravity. Such artificial gravity would also solve many of the problems to do with the body's response to weightlessness. But these problems seem, according to the Russians, to be small compared to the potential which Salyut 6 has shown exists for manned space stations. In September 1978, when the second Salyut crew broke the previous space endurance record (their record was later shattered by Lyakhov and Ryumin), Soviet officials stated with unusual frankness that Salyut was the precursor to manned Soviet missions to the planets. It seems that such missions are part of fairly near-term Soviet planning, whereas they are only envisaged by the United States in schemes too far ahead to have a definite date fixed. The main difference between Soviet and US space plans may be the same on the interplanetary scale as it is in Earth orbit, the Americans developing sophisticated unmanned space probes while the Russians concentrate on manned missions. It seems from Soviet pronouncements by cosmonaut Alexei Leonov – the first space walker and a member of the Apollo-Soyuz crew – and others that a permanent manned space station in a low Earth orbit is well within the scope of present Soviet space plans. NASA Administrator Robert A. Frosch said in early 1979 that a Soviet station of that kind would be regarded as a 'serious challenge to US interests.' A couple of months after he spoke, the Soviet Cosmos 1100 and 1101 launches took place, involving two large space vehicles again launched by Proton rocket. Both vehicles returned to Earth after less than one orbit, like previous pairs of Cosmos satellites including 881 and 882 and 997 and 998. These are thought to have been trial launches of large 'man-oriented' space vehicles. The Soviets are also known to be improving the Soyuz spacecraft, for instance, it is thought, by using solar panels on them. This apparently minor change would allow the time they can remain in orbit to be extended before they have either to dock with a Salyut station or return to Earth, since that time is now limited by the batteries they can carry. This might have prevented the abortive Soyuz 25 trip in October 1977.

At the beginning of 1980, it seemed that Salyut 6 was all set to be reactivated, and that the political books were to be balanced by cosmonauts from Comecon countries which have not previously provided Salyut crewmen being allowed their first trip up. These include Vietnam, Cuba, Mongolia, Hungary and Rumania. Vladimir Shatalov, the USSR's chief of manned spaceflight, implied strongly in October 1979 that there could not be too much of a hurry over the first post-Salyut space station, simply because each two-month trip to Salyut produces data which needs two years of interpretation. But he implied too that the Soviet space managers are working hard to reduce the lead times needed to make use of the Salyut findings.

The Salyut series, especially Salyut 6, has restored the Soviet manned space effort to approximate parity with NASA's efforts at a time when the European Space Agency's efforts – especially with its Ariane launcher-for-hire service – are upsetting the status quo of US dominance in unmanned flight. This is happening at a time when satellite communications, remote sensing and other satellite applications seem set to be a long-term boom business. From a position early in what was called the space race, when the USSR orbited the first satellite, put the first man in orbit, put the first three-man crew in orbit, managed the first space walk and sent the first probe to the Moon, the Russians seemed to have taken second place to the USA, with its manned Moon trips and brilliantly successful planetary explorers, until the end of the 1970s.

It would now be absurd to suppose that the Russians plan to let that position become permanent. As well as schemes for manned planetary missions and unmanned trips to the outer planets, there may well be further space co-operation with the French. The latter are already participating in unmanned Soviet space experiments, and there may be a French astronaut on a Soviet space flight by 1982. Soviet and US space projects involving astronauts from East and West Europe are just one symptom of the increasing variety of people going into space. At a less developed stage are initiatives in other countries which could eventually lead to spaceflight being available very widely, perhaps even to people who have not undergone the

lengthy formal training which astronauts have so far received This apprenticeship seems to be the prerogative of major national space programmes. For instance, in early 1980 it was finally announced from Peking that Chinese astronauts are under training, in a major manned spaceflight development programme which had already involved recovering small mammals like mice and dogs from suborbital lobs. The use of dogs may be a hangover from old contacts with the Soviet space programme. The early stages of US space exploration used monkeys, which are biologically closer to man. This may have been part of the reason why US astronauts had a less traumatic time of it on their early space flights.

The Chinese manned space programme is operating in tandem with an extensive unmanned programme involving satellites for reconnaisance, meteorology, and communications. There seem to be weak points in the programme. Thus the Chinese plan to buy two TV broadcast satellites in the USA and have them launched by the space Shuttle in 1984. But in March 1978, 1985 was set at a major Chinese scientific meeting as the date by which 'skylabs and space probes' should have been launched. The term seems to imply manned flight. If it is the intention to have full-scale Salyut-type laboratories in orbit by then, the Chinese will have to move fast, learning all the lessons which Soviet and US space experience can provide. It is unclear exactly what the Chinese manned space programme aims to achieve, in contrast to the highly practical unmanned programme already being implemented by the Chinese. It is sensible to assume that space manufacturing is under consideration, as well as Earth observations which cannot easily be automated, but beyond that the Chinese manned programme is pretty much a black box.

Chinese-style secrecy – whether for military reasons, or just because it comes naturally – is the last thing encountered with the smallest possible unit of space exploration, the one-man operation approach to manned space flight. It is far too early to tell whether they will get anywhere, but several small firms have been set up lately to put people into orbit without the big forces involved in, say, the Space Shuttle. It could be that manned flight will

eventually join satellite communications and other space applications by being turned over from government agencies to private enterprise once the risks have been taken at public expense and the prospect of profits is firmly in view. US policy is for NASA to spin off sectors of its space exploration activities to other government agencies, like the National Oceanic and Atmospheric Administration in the case of remote sensing, or to private enterprise, once they become viable without state funding.

It will be a long time, perhaps infinitely long, before that happens to manned spaceflight. So what some entrepreneurs like Bob Truax of Saratoga, California, are doing is essentially to get into private spaceflight a step ahead of the timetables which government has in mind. His firm, Truax Engineering, has already been in on some quirky projects like a rocket-propelled motor bike for stuntsman Evel Knievel. Before going private, he also headed up the Pentagon's space effort in the 1950s – some of the projects he was in are still classified – and was influential in the Polaris submarine-launched ballistic missile programme and the Mercury flights.

So far, Truax won't offer to put you in orbit, but he will offer the ride of a lifetime – a million dollars for a sub-orbital lob into space like Alan Shepard and Virgil Grissom, the United States' first astronauts, made in Gemini 3 and 4 in 1961. So far there are two possible takers, a Mexican tortilla millionaire and a rock music manager. Plenty of other people seem willing to enthuse without producing their chequebooks, and Truax thinks that they may well become a lot readier to part with money once the project looks nearer to happening.

Although Truax has done a lot of the engineering himself, the basis of his 'Volksrocket X-1', as he calls his prototype, is scrap from government surplus dealers and scrapyards. Old Saturn launchers rarely appear in the classified advertisement columns. But it is possible to pick up electronics for instrumentation, tanks which can – with modifications – hold liquid oxygen, and other bits and pieces for the Volksrocket. What cannot be bought, like the more complex parts of the plumbing for the fuel system, can be fabricated by a man who was in the space race – with

the armed forces – before Werner Von Braun knew that the Americans were interested.

Truax's plan is to launch the rocket from dry land, probably on the West Coast of the USA, out over the ocean. The X-1 rocket is a single stage affair and the one motor would fire until an altitude of about 40 km was reached. Then it would coast until it reached a height of about 80 km, at the top of the Earth's atmosphere. Then it would re-enter the atmosphere and be recovered at sea, ready for re-use. Truax regards the space shuttle as a monster too costly, too clumsy (it has to be landed without power) and too complex. His rocket will not put anyone into space for long – all it'll do is give the astronaut a great view of the Earth and stars for a few minutes. To do more it would have to include all the complexities of re-entry rockets, stage separation, and precise controls. In the Volksrocket, all the astronaut does is sit tight in a nose cone made out of an aircraft fuel tank and hope for the best, although he has a few last-ditch emergency controls.

A venture like Truax's isn't going to lead to any space stations. But in the end, home-built initiatives like his may become important if people do begin to spread themselves throughout the solar system. Gerard O'Neill, the prime mover behind the idea of space colonies in Earth orbit (of that, much more later) has proposed that, provided there were some official safety and reliability checkups, there need be no reason why people should not build their own spacecraft for voyages into the solar system. Starting from one of O'Neill's space colonies, the precision operational timing and the great forces necessary for getting away from Earth gravity would be unnecessary. A spacecraft built out of aluminium and welded into a sphere (aluminium is easy to weld and X-ray techniques for weld testing are established) could be used to take units from family size upwards to the asteroids. If that ever happens, Truax will have been in the vanguard much as Von Braun was in terms of big-rocket trips to orbit and to the Moon.

Before that can happen, both public and private spaceflight will have had to take giant steps. The latter, as we have just seen, is only at the beginning of any viable life it might have. But the public sector is a good deal better

established The USA and the USSR have consistently challenged each other in manned spaceflight for a number of reasons One is military some of the Salyut stations have been used for military reconnaissance, like many unmanned spacecraft Another motivation, of course, is the prospect of eventual large profits from space manufacturing and from space colonies. And there are already many practical uses for space which make it well worth the Americans' while to put resources into it. But at the moment, US manned spaceflight has hit a rough patch (The American decision to get out of one-shot rockets and offer only the space Shuttle has been implemented only very slowly, because of all manner of technology problems, and with the Shuttle's problems, the US manned programme came almost to a halt. For instance, the 1980 NASA launch schedule as published late in 1979 has only one manned flight the first Shuttle launch – in contrast to eight hire-and-reward launches for communications contractors and other space applications users, and one unmanned science probe launch. Despite this, and many years out of the headlines for manned spaceflight, it is clear that people still want to go into space In autumn 1979, 2937 men and women applied for between 10 and 20 openings for astronauts advertised by NASA. In time, NASA will need many more astronauts if the space Shuttle gets going as planned The distinction between manned and unmanned flight will then burst like a balloon: although there will be many unmanned satellites, they will be placed into orbit by a flight crew which will also bring the winged part of the Shuttle back to Earth

The Space Shuttle described more fully in this book's first chapter is the third generation of US space launchers, following on the early launch rockets for small satellites – manned and unmanned – derived from military rockets, and the huge, expendable Saturn rocket which was used for the manned trips to the Moon and into orbit in the Apollo space missions. Later it also launched Skylab, the USA's closest approach so far to a full manned space station.

The development of US manned spaceflight roughly parallels Soviet experience, with rockets of larger size putting more and more men (a woman is promised for the

early stages of the Shuttle programme) into space for ever lengthier missions. It began in 1961 with the first two manned Mercury flights, Mercury 3 and 4 The shots were made with a Redstone rocket, a large but not inter-continental military missile. They carried Alan Shepard and Gus Grissom respectively into space for a few minutes each in much the way as Bob Truax proposes to do for tortillo millionaires and others with plenty of spare cash and an enthusiasm for space. Their flightpaths took them into weightlessness for about a third of their quarter-hour flights. Critics of the early Mercury flights were quick to point out that they were a very far from ideal way for America to get its first rides in space. For one thing, the Redstone rocket could only just lift the capsule plus astronaut – backup equipment was minimal. And the design was hardly well tested. When Grissom splashed down, an explosive-loaded hatch cover installed to allow a quick escape in case of emergency blew out for no good reason and he had to swim clear. The capsule sank and he was picked up by helicopter. The accusation that the Mercury flights had been cobbled hastily together as a political response to the first Soviet manned flight a month before Mercury 3 seemed well-founded to many. The easier unmanned Mercury flights had also gone badly. But after this unpropitious start, Mercury started to deliver. It did so with four true orbital flights in 1962 and 1963, numbered Mercury 6 to 8; Mercury 5 was a two-orbit flight with a chimpanzee, Enos, like Mercury 2 which had flown with chimpanzee Ham four months before Shepard's flight. Mercury 6, a five hour flight in February 1962 took John Glenn on three Earth orbits the first American to make it. There were fears about whether he would get down again when the heat shield, designed to keep astronaut and capsule from burning up on re-entry, seemed to be loose, but in the end all was well. On Mercury 7, three months later, Scott Carpenter was retrieved after only another five hours and three orbits in space, having burnt up an excessive amount of his fuel steering the Mercury capsule in orbit to improve the view. He finished up hundreds of miles away from the recovery crew waiting for him in the Atlantic, in an episode which could easily have ended in

tragedy It was left for Mercury 8, Walter Schirra, and October 1962 for Mercury to work properly in a six orbit, nine hour flight with a splashdown only a few miles from the waiting US Navy Next year in May 1963 – the Americans were confident enough to put Gordon Cooper into space for nearly one and a half days, and 22 orbits Towards the end of the flight, the automatic controls started to show signs of instability and the air purification seemed to be tiring, with carbon dioxide levels in the spacecraft rising. Cooper, to the intense envy of his astronaut colleagues, virtually had to steer the capsule back to Earth himself, in contrast to his predecessors who had had about as much say in the flying of their ships as Enos and Ham. All went well, but it was not a propitious end to the Mercury programme. Perhaps similar stories could be told by insiders of the reality behind the USSR's Vostok flights, which were taking place at the same time. NASA put the problems Mercury had had behind it (the programme had, after all, yielded a lot of science and engineering information) and proceeded to the two-man Gemini programme.

The first manned Gemini flight, Gemini 3 there having been two unmanned test flights did not occur until just over two years after Mercury 9. After that, the Gemini programme went off at a rip-roaring pace, with Gemini 12, the last of the series, splashing down in November 1966, just 20 months and ten spaceflights later. The last five Gemini flights have a further significance they were joint operations: Agena rockets placed into similar orbits were used to provide the USA's first space rendezvous. This space docking practice was the precursor of the complex docking operations later carried out in the Apollo Moon landings and elsewhere in the US space programme.

The Gemini programme did not, at last, provide NASA with trouble-free spaceflight. One of the early flights in the series, Gemini 6, was postponed when the Agena target went missing in space. Instead, Gemini 6 was launched just after Gemini 7 and the two spacecraft made a close approach to within a few feet, which has to be regarded as making a good thing out of a bad one. The Gemini 7 flight lasted nearly a fortnight, the longest US spaceflight until

the record breaking Skylab 2 in 1973, which exceeded even the triumphant Moon flights in length. Other Gemini flights had more problems. Gemini 4 had to be brought back to Earth manually and landed many miles from the target point. Gemini 8 got into orbit long enough to dock with the Agena target, but the pair of spacecraft then began to tumble and the mission had to be aborted. The problem was caused by a thruster which would not cease thrusting to order – the capsule's own rockets had to be used to get Gemini 8 out of trouble, and back to Earth, just 11 hours after launch.

Later Gemini flights worked out better – US space walks became longer and ended with three, totalling over 5 hours, carried out by Buzz Aldrin (of Apollo 11 fame) in Gemini 12. The first experiments in artificial space gravity were carried out by spinning Gemini 11 and the Geminis also carried the first true computers into orbit to carry out calculations for the rendezvous exercises and other in-flight problems The Gemini computers were forebears of the Apollo Precision Navigation and Guidance System and other later, successful computers for complex calculations in space.

All this left NASA finally in a position to fulfil President John F. Kennedy's 1961 objective of putting a man on the Moon by the end of the decade. As Kennedy put it, space was a new ocean upon which the USA most definitely ought to sail. But for the decade after his speech eight years before the first Moon landing occurred – NASA concentrated its efforts not on the ocean but on the nearest island to shore, the Moon. Manned flight to the Moon was chosen as the way ahead for the US space programme, instead of the development of manned space stations, for a number of reasons. The most important is that the Moon is an easily comprehensible target even to cynical congressmen, elected from benighted states far away from aerospace manufacturing centres. Scientists, also, were able to make a strong case for taking a close look at another planet. But it seems that the simple magnetism of the Moon as a target was irresistible throughout NASA and everywhere else that mattered in terms of US political power. Any other objective might have been politically

vulnerable, but the Moon project meant swelling budgets for NASA throughout the 1960s, even when the US taxpayer was also paying on the grand scale for US military involvement in South-East Asia.

The device chosen to make Kennedy's lunar ambitions into reality is most economically called Apollo-Saturn. The two words hide as much power and complexity as has ever gone into a high-technology project. The Saturn part is easier to understand – it is, of course, a rocket, one of the series of rockets which made Dr Werner Von Braun into the US space world's most famous figure, apart from the astronauts, far outshining the NASA Administrators who were his nominal bosses. The Saturn 5 rocket used to put Apollo on the Moon and later Skylab into orbit was a massive three stage affair weighing some 3000 tonnes, as much as a modest ship except that the 3400 tonne thrust of its main engines sufficed to send it straight upwards. Most of the muscle of Saturn lay, necessarily, in its first stage, whose five huge engines, burning about 13 tonnes of fuel per minute, took Apollo through the densest 60 kilometres of the Earth's atmosphere. After this the first stage – accounting for over 40 metres of the 110 metres height of Apollo-Saturn at launch – would fall back into the Atlantic. The second stage was similar but a lot smaller – another five engines but only 500 tonnes of thrust and about 20 metres of length. After it had used its fuel and fallen away, the need for big thrusts and huge rockets was gone. From now on, with Earth's gravity overcome, only minutes into the mission, small thrusters were used for comparatively low-energy tasks such as putting the spacecraft into a trajectory from Earth to Moon.

The third and last Saturn stage thus had a task involving less push (just over 100 tonnes) and more subtlety. The single engine was used for two main tasks. The first was to put the Apollo spacecraft into an orbit around the Earth. After this the engine was shut off, a thing which was impossible with the first two stages once their engines were ignited. A second firing placed the Apollo spacecraft on the way to the Moon after a small number of Earth orbits. After this, the third stage was also abandoned, either cast loose in the general direction of the Sun or made use of for

science experiments.

At this stage, the 110 m Apollo-Saturn spacecraft – nearly six times the height, at launch, of the big Minuteman missiles on which the US land-based nuclear deterrent is based – had been whittled down to just three components – the lunar module, the command module and the service module – with a total length of under 20 m. The command module was the nerve centre, housing controls and Apollo's communications with Earth. The service module was essentially an engine, used for mid-course corrections on the way to and from the Moon as well as for 'burns' computed to put the spacecraft into an orbit around the Moon and to get it out again en route for home. The lunar module's function was obvious – it was used for the descent to the lunar surface, and the upper part was used to leave the Moon and rendezvous with the rest of the spacecraft for the return journey to Earth.

If all this sounds complex, it was. The idea of the Apollo mission in the approximate form in which it was eventually carried out was finally formulated in 1960, but not before earlier schemes had been thought of which would have used one large rocket to descend to the Moon's surface and blast off again, avoiding the need for complex manoeuvres like the docking in lunar orbit. Analyses carried out before Apollo 11 indicated that this was the point in the mission at which disaster was most likely to occur. As it was, Apollo was almost free from misfortune. The Moon was invaded by stages – Apollo 7 was the first manned Apollo flight, involving the command and service modules. It stayed in Earth orbit. At Christmas 1968, two months later, the same ensemble was taken around the Moon, involving the on-board computer in calculating the retro-rocket 'burn', applied with the spacecraft out of radio contact with Earth behind the Moon's far side. This was regarded as another potential crisis point in the Apollo idea. As it turned out, both operations always went well. Apollo 9, in March 1969 (for Apollo went on at almost the same breakneck launch rate as Gemini) took the lunar module into Earth orbit as well, for trials of the docking sequence. May 1969 saw the Apollo 10 mission, with two frustrated astronauts flying the lunar excursion module in an orbit bringing it within

less than 20 km of the Moon's surface and doing everything except land. That, of course, was on the agenda for July 1969's Apollo 11 flight. Despite some alarms with the descent controls, the landing went sweetly, as did other Apollo Moon trips up to Apollo 17, with the near disastrous exception of Apollo 13.

The Apollo 13 problem had nothing to do with the tricky rocket burn to put the spacecraft into lunar orbit. It was a straight technology problem. An oxygen tank explosion caused service module rockets to fail. The problem was solved by using the lunar module to provide rocket thrust to swing the spacecraft round the Moon (no landing) and back to Earth. A five year NASA inquiry revealed that an oxygen tank had blown up because its heaters, intended to work intermittently, had switched themselves on permanently. When the service module was finally abandoned just before re-entry, the astronauts took a long look at it and were amazed at the damage it had sustained. That sort of accident could equally well have happened at an early stage in the Apollo programme, perhaps with terminal results for America's lunar ambitions. But with successful Apollo flights already carried out, including two Moon landings, Apollo 13 did not halt the programme. NASA was able to make the best of a bad job by pointing to the flexibility in the Apollo technology which allowed the astronauts to be got back to Earth despite the terrifying failure of the spacecraft.

As Apollo went on, the missions became more effective, carrying more scientific experiments and taking big-wheeled Moon Rovers to the Moon, allowing the distances the astronauts could travel on the Moon to be drastically increased. Whether Apollo was value for money – about $25 billion dollars – is a judgement which, a decade after the event, readers can make for themselves. But if there was still such a thing as a space race, there can be no doubt that Apollo put the USA ahead in it. The next hurdle in the race involved America returning its attention to Earth in terms of manned spaceflight. This involved the USA's first manned space stations. The initiative was called Skylab.

Skylab eventually came to a bad end in 1979. It re-entered the Earth's atmosphere and scattered parts of itself

over some less frequently visited parts of the Western Australian outback. Publicity had implied that the re-entry might be a world catastrophe, with a city centre devastated, or that - on the other hand - the lab might break up in the upper atmosphere and produce nothing worse than a few small pieces of metalwork falling into the ocean. In the end, after allegations that Skylab's orbit had been altered to minimise the chance that it would fall on the United States, the end result was nearer the low-impact end of the predictions. The pieces were so widespread that they would have been hard put to cause much of a catastrophe wherever they had landed. In the meantime, the Skylab experiment had proven very worthwhile for NASA's future planning. Although there was only one Skylab, placed in orbit in 1973, the NASA nomenclature referred to the launch as Skylab 1 and to the three crew missions to the laboratory as Skylab 2, 3 and 4. In its six years of life, Skylab was visited by its three-man crews for only 28, 59 and 84 days for Skylab 2, 3 and 4 respectively, meaning that the total utilisation of the lab was low compared to the record send up by Salyut 6. Skylab was launched with a Saturn 5 rocket, the same huge vehicle used to launch Apollo, and weighed almost 100 tonnes upon launch. It was the size of a railway freight car.

Skylab's experimental agenda seems to have had a lot in common with the work carried out on Salyut 6, with the important difference that, as the name implies, Skylab's emphasis was more firmly on science. In the main, Skylab was an observatory. John A. Eddy of the USA's High Altitude Observatory wrote in *Applied Optics* (a special Skylab issue, published in April 1977 and quoted in *Sky and Telescope*) that 'More than anything else, Skylab was a laboratory of optical instruments, in the broadest definition, spanning the full reach of the electromagnetic spectrum from hard X-rays to radio waves. It was surely the largest assemblage of lenses, mirrors, reticles, prisms, windows, filters, gratings, cameras, films, photomultipliers, computers and electro-optical systems ever lofted above the surface of the Earth.' That is saying something, bearing in mind the snooping potential in modern spy satellites. And as well as the optics, there were

medical, engineering and other types of experiment

Skylab finished up as a great success in terms of the scientific results it obtained – gained by training all those pieces of optics on the Earth and on astronomical objects – and in terms of giving America experience of extended space missions. But it could all have ended in fiasco at an early stage. Skylab's launch on 14 May 1973, seemed normal enough to the casual observer, but the instrument readings telemetred back to Earth from the spacecraft showed that when it had been in flight for just 63 seconds, a small vibration ran through the ship, caused by stresses set up as Skylab and its Saturn launcher forced a way through the atmosphere. The vibration was the main cause, it seems, of extensive damage sustained by Skylab on its way into orbit.

Skylab was in orbit before the problems started to become apparent. At first all went well as the Skylab telescope mount (confusingly enough called ATM for Apollo telescope mount) and its four solar panels were swung away from the body of Skylab. The 361 cubic metre Skylab consisted of the 15 m long, 7 m diameter workshop where most of the living and working was carried out, a small instrument unit, an airlock module which was used for controlling the Skylab environment and for exit and entry for spacewalks. There was also a docking adapter to allow the crew ascent and descent vehicle – the Command Service Module – to dock with Skylab, plus the ATM.

The problems began after the ATM had been deployed. First, signals arrived which seemed to show that the workshop's solar panels, which were intended to supply most of the energy for the lab, had not been deployed properly. The fault, it turned out, lay in the heat shield designed to keep both meteoroids and the full strength of the Sun off the workshop. The shield should have been deployed in space by being pushed away from the spacecraft body by a few inches. In fact, it was deployed in mid-atmosphere and torn away in the slipstream. In being torn away, it had taken solar panels with it. A plan was put together to run Skylab on ATM power only, and to improvise a heat shield which the Skylab 2 crew, launched 15 days after Skylab itself, could carry into space. Before

the astronauts went up, the temperature at the surface of Skylab reached 165°. Although it was a lot cooler inside, this was clearly too hot for people to work. It also risked medical supplies and canned food rotting, and even plastics giving off poisonous gases.

The story of how the Skylab launch problems were overcome is one of the most remarkable in space exploration, as remarkable in its way as the much-trumpeted rescue of Apollo 13. First, Skylab's nitrogen powered rockets were used to turn the lab so as to minimise its profile for sunlight, bringing down the temperature to about 50°. Liquid nitrogen was one of Skylab's most precious and critical resources - before the arrival of the Skylab 2 crew, it had to be used to keep the different parts of the craft from boiling or freezing because of being continually in or out of the direct sun. It also had to be used to stabilise the spacecraft in position when its potentially poisonous atmosphere was vented. The astronauts were equipped, coal miner style, with poison gas detectors and gas masks. In the end, the Skylab 2 crew managed to deploy three sunshields and unshipped the jammed solar panel with an heroic space walk. Within days of their arrival, high class ultraviolet pictures of the Sun were being obtained with a Harvard Observatory telescope on the ATM. They also started remote sensing activities while over the United States.

The Skylab 3 and 4 flights were less adventurous than 1 and 2, to universal relief, although the Skylab 3 crew developed nausea for about a week and were nearly brought home when a gas thruster leaked persistently, leading to fears that it would exhaust itself, and the command and service module lose its manoeuvrability. But the Skylab 3 and 4 crews managed to do a great deal of science, taking thousands of photographs of the Earth and astronomical objects, including one of the nine-day wonders of the early 1970s, Comet Kohoutek. They also demonstrated that spiders can spin webs in space, in an experiment suggested by some US schoolchildren and carried out by two spiders called Anita and Arabella.

It may well be that the scientific data obtained by Apollo, Skylab and the rest of the US manned space programme

could have been got more readily without involving astronauts at all. The big exception, of course, is the information obtained about how man himself adapts to long periods in space. That information is vital input to NASA thinking about the future for man in space. At the moment this centres around projects – being studied by NASA and its contractors – for large, permanently manned, space structures. There is little telling when these plans will come to fruition. The NASA budget for the 1981 fiscal year, for instance, allocates some funds for investigatory work but none for anything but the smallest-scale engineering development. Nearly half the $4.5 billion dollar spend announced in January 1980 is going on the Space Shuttle, regarded in the US (by everyone except Bob Truax) as the essential precursor to big space settlements.

The NASA studies vary in immediacy from long-term work on huge 'manned facilities' to applied studies of structures which could be in orbit this decade. According to *Aviation Week* in 1979, the term space station is being abolished because it is politically contentious, and according to Reginald Turnill's *Manned Spaceflight*, the term space colony is being phased out because colonies, too, have the wrong ring in too many ears. One project actively being considered by General Dynamics, one of the big US aerospace contractors, is for a large platform to be placed in geostationary orbit (where space is becoming scarce) to house telecommunications, meteorology, remote sensing and other types of facilities. This would save on space and allow economies of scale because the Space Shuttle should mean that one launch will be able to put missions into orbit which would previously have required several. But the real savings could come later on – it will be possible with the Space Shuttle to retrieve satellites from orbit for repair or replacement. This will be all the easier if there is one large platform rather than several small satellites such as are now used. The type of platform being studied by General Dynamics would probably be unmanned, but a stage would be reached when it became worth while to put a maintenance man on it full time instead of sending one out each time something needed doing.

Large space stations were being studied very intensively at NASA in the mid 1970s, but were stymied by lack of money and because the space station idea seemed insufficiently respectable for serious project analysis. By 1979, things were moving again, with studies of power systems, life support equipment, and other essentials. At that stage, NASA was thinking in terms of space platforms to be manned intermittently, visited by space Shuttle missions. An idea of the size they had in mind (at this stage, it was all at the level of thinking about carrying out studies) can be gained from the power levels being contemplated, about 250 kw, as against the total of about 25 kw used by Skylab. (A bar of an electric fire is about 1 kw.) In the late 1980s NASA thought, permanently manned modules could be added to the part-time occupied units already in orbit. These platforms — with astronauts carrying out science experiments while unmanned electronics get on with activities like satellite communications — are scarcely glimmers in NASA planners' eyes. Some of that may start this decade. Every factor from inflation to the success of the Space Shuttle may mean delays. And there are no signs that the US Congress is going to regard it as an urgent priority very rapidly. One thing which might guarantee a speed-up would be an intensification of the USSR's Salyut programme.

Beyond this decade, of course, things become even more speculative. Perhaps our rulers will simply decide that space and man do not mix, and space programmes will be reduced to a rump of high-utility projects like satellite communications. That course of development seems unlikely to this author, for many reasons: the most irresistible would probably turn out to be the military imperative, one of the driving motors of rocket and space programmes for some 50 years.

If space is to be permanently inhabited, the space platforms being planned by NASA can only be a first step. they would, for instance, almost certainly be too small to produce their own food. Their lack of green plants would mean that an ecosystem could not be set up to allow them to recycle their own air. What is needed if living in space is to become a real prospect is space settlements with enough

people to command at least a measure of biological and social independence of Earth, to be more than a 'space colony'. This would require thousands of people and hundreds of hectares of area. The startling thing is that detailed plans for such settlements have been drawn up, largely in the United States, by a group surrounding Professor Gerard K O'Neill, a physics professor at Princeton University. He and a colleague, Brian O'Leary, have published over 30 books and articles on the space colony idea, dealing with everything from the way they would be manufactured and run to the social aspects. Many observers are unconvinced, but among those who have paid close attention are the US Senate's Aerospace subcommittee and numerous scientific meetings such as a series of American Institute of Aeronautics and Astronautics Princeton University meetings on space manufacturing

The space colonies idea (O'Neill still uses the term despite Turnill's squeamishness) arose from teaching sessions O'Neill gave for his undergraduates in 1969. He wanted to let his students loose on an idea which they could think about constructively with limited mathematical and physical tools, and which would let them see science and engineering in a more positive light than the average US student did then The furore over high technology warfare in South East Asia was at its height. The starting point was the question 'Is the surface of a planet really the right place for an expanding technological civilisation?' and the numbers led quickly to the answer no In the intervening years, O'Neill's conviction seems to have deepened that space colonies are the best way out of an energy and environmental mess which we are getting into here on Earth. The second and third chapters of his book on the matter, *The High Frontier*, are devoted to analysing the problem, and conclude that Earth is best kept for non-industrial activities involving a minimum of people, quoting pessimists like Robert Heilbroner who take the view that man on Earth is already in a pretty irretrievable mess.

Unlike Heilbroner, O'Neill thinks he knows how we are going to get out of the mess. He says that the answer emerged rapidly in his Princeton class. A structure several

miles across, big enough to have Earth gravity and contain an atmosphere, can be built sufficiently easily that 'more than a thousand times the land area of the Earth' becomes available for expansion. In addition, a look at the near reaches of the solar system showed where the first such structure, at least, has to go, the Langrangian points, at the third corner of an equilateral triangle with the Moon and the Earth at the other points. Later, O'Neill seems to have decided that a conventional Earth orbit would be a better bet. The key to space colonies, in O'Neill's view, is to start small and clever, and above all to minimise the investment needed and make it start paying for itself at an early stage. The first big problem, of course, is gravity. The Earth's gravity field is, in effect, a well out of which anything taken into space must be dragged. So O'Neill proposes that we should drag raw materials not from the Earth's well, but from one of the shallower, less energy-demanding wells which are also available. The choice is between the Moon - which is nearby and whose chemistry is comparatively well-known - and the asteroids, which have negligible gravity but which are further off and which might prove chemically less suitable.

Moon material, according to O'Neill, will do just fine for space colony construction. For one thing, the colonies O'Neill envisages will hardly use enough material 'to keep one bulldozer occupied'. The Moon has about the surface area of Africa, so this hardly amounts to rape. The Moon material could be smelted, O'Neill thinks, in furnaces in orbit, powered by sunlight. These would provide oxygen to breathe, aluminium to build with, silicon to fabricate solar cells, and other useful elements Lunar soil, like terrestrial lavas, also contains a lot of glass. This could be used to knit fibre-glass containers at the Moon's surface, in which the Moon soil would be sent to the budding space colony. It could also be used as glass at the colony. In the economics of O'Neill's colonial ambitions, nothing can be wasted. The slag from the orbital furnaces would be pressed into service for radiation shielding, for growing plants, or for 'reaction mass,' in other words to be thrown out of the back of rockets which expel cool solids instead of hot, expanding gases.

All this would involve one station in space and another at the lunar surface. O'Neill points out that the key requirement on the Moon is to get as much as possible of the workings under cover and in air. Otherwise the work has to be done in space suits and becomes problematical and dangerous. The central feature of the Moon station would be the 'mass driver', of which two small-scale models have already been built. NASA is supporting work on the device, as it was in 1979 supporting a General Dynamics study on the use of lunar materials in geostationary spacecraft. This aims to find the size threshold beyond which savings could be made by using lunar materials instead of bringing everything from Earth. It seems sensible to assume that the answer will be well short of a full O'Neill type colony for 10,000 people, where bringing everything from Earth is apparently not an option. According to Brian O'Leary, O'Neill's colleague, the lunar mass driver would be 'a long and narrow machine which converts electrical energy into kinetic energy,' accelerating the Moon material to the space colony site. The material would be accelerated in buckets magnetically levitated from the ground containing superconducting coils. There would be stationary coils in the mass driver. If the current in the coils is fluctuated properly, they will both pull and push the bucket along the length of the driver until its contents are thrown out with the desired acceleration. The mass driver is, in the view of some critics, the real weak link in the system - it would be a very demanding piece of electrical engineering to make work on the Moon or anywhere else. The first two prototypes are on a very small scale, with mass driver 2, built in 1978, capable of accelerating a 13 centimetres diameter bucket to 112 metres per second over its 2.5 metres length, that is equivalent to an acceleration of 5000 metres per second per second.

The asteroids are terra nova in every sense, but although most of them lurk between Mars and Jupiter, some come near to the Earth and they could provide raw materials like carbon, hydrogen, nitrogen and free metals. Their materials would be retrieved with a mass driver, again, and it is possible that the lower asteroidal gravity would make the economics attractive in comparison with using Moon

material. A NASA asteroid resource study group has looked in detail at the possibilities, and at the astronomical work needed to find out about the composition and distribution of asteroids which might prove suitable.

O'Neill agrees that it is vital to make the colonies, even his 10,000-soul 'Island', pay for themselves. His modest proposal for doing so involves solving the energy crisis by selling sunlight to Earth. This proposal is clearly attractive to governments and others who have a strong interest in huge amounts of cheap, harmless energy. O'Neill's curves show that the cash-flow for Island 1 could become strongly positive (i.e. big profits could be made) within decades, but payback would not be complete, according to his evidence to the Senators, until 24 years into the programme. That is a long time even for a project which is a sure-fire winner. Even though the cost is modest compared, say, to commercial production of electricity by hydrogen fusion, the economics are not dazzling. The whole idea could be torpedoed if investment capital for energy projects is ploughed not into huge schemes like nuclear power or electricity from space but instead into small-scale energy sources like wind power. The energy history of the 1970s – rapidly rising prices giving rise to vastly reduced growth in energy use – is hardly good news for O'Neill's plans for financing Island 1.

If Island 1 is built, however it pays for itself, what would it be like? It is the smallest of O'Neill's colony designs. A later 1972 design, Island 3, would be a 10 km long cylinder, 2 km in diameter, housing a million people with space for lakes, mountains and the like. There could even be rivers running down the hills, towards the outside of the island. Island 1 would also have many startling features for anyone used to the Earth. It would, for instance, make its gravity by spinning. So a walk towards the centre of its 1.6 km circumference sphere – any walk up a hill – will take the walker nearer its centre and into less and less gravity. The rotations will be at a rate of about two per minute to produce Earth gravity at the equator – going towards the poles will also take one into lower gravity. Much fun could be had by hang-gliding enthusiasts, who could fly through varying gravity fields in a matter of a few minutes.

Island 1 as O'Neill describes it seems idyllic, although so do the worst housing estates when an architect who is going to take his fee and live somewhere else is talking about them. Each family could have its own large apartment with sunlit garden (it is easy to set things up so that sunlight imitates Earth conditions closely). Island 1 has boundless scenic possibilities, as seen by O'Neill. The equator 'seems an ideal location for a wandering, shallow river, opening into occasional deep pools for swimming. The shoreline beaches can be of lunar sand, and perhaps at a little distance, surrounded by greenery, there can be paths for bicycling, walking and running.' (One suspects that O'Neill is a secret jogger.) Island 1's pressure vessel would weigh about 100,000 tonnes — as much as a big liner, as O'Neill puts it, and a lot less than a modern supertanker. But soil, machinery, and air would total several times as much. There are many industrial possibilities at Island 1. One which sociologists ought to approve of, as well as workforce and management, is that machinery can be operated full-time with nobody having to work the night shift. It is easy to organise Island 1 into three villages, each eight hours apart on the clock. And on Island 1, the machinery must work full-time, both to keep the place alive and to make it pay for itself.

O'Neill's sums have shown what might happen if one were to proceed from Island 1 to a later 140,000 head Island 2 and the million-head Island 3. By year 10 the population in space would be 290,000 people (Island 1 plus two Islands 2). By year 15 it would be 1.5 million and by year 35, 7.3 billion, nearly twice the present population of the Earth. The figures assume the sort of productivity obtained in industry on Earth. But they seem to show that, as O'Neill puts it, 'the productivity we have achieved already on Earth, when employed in the energy-rich, materials-rich (he might have added low-gravity) environment of space, could lead within less than two generations to a production-rate of new land great enough even to accommodate the population increase rate of Earth.' The present author is not a great believer in energy crises (all they seem to require is more conservation and more making use of the energy now going to waste all around us)

or population crises (if the world worked properly, everyone born would be a potential producer, not a drain on resources) But O'Neill's vision is powerful and his numbers are not obviously mad: sooner or later, something like he has envisaged will probably be tried.

I hope it is done as a fine project on its own merits, not under *force majeure* because of a perceived excess of people. I don't know whether I'd like to live on Island 1. I do like real mountains, and real snow under my boots, not heaped-up Moon soil. If O'Neill's sums are right, I couldn't afford to visit Earth more than once every few years. But the Islands would certainly boast virtually every amenity except solid Earth, from orchestras to a man-designed ecology designed, for instance, to give forests without mosquitoes. On balance, perhaps the O'Neill islands are the habitat of the future, and the surface of a planet really is a lousy place for a developing high-technology society.

The key space colony problem may well turn out to be not physics but biology. The Space Shuttle seems likely to provide a reasonably priced way of getting essential equipment to the site chosen for an O'Neill space colony. There are many question marks, but they seem small, mainly at the lunar end of the operation. Building of the colony seems not to involve any immense feats of engineering by the standards of the late twentieth century. Given the political will, the physical problems seem small compared to those inherent in, say, commercial-scale fusion of hydrogen, which is now the subject of several large-scale projects worldwide.

Biology is a knottier problem. One group of biologists brought together by the Californian magazine *Co-Evolution Quarterly* to take a close look at 'ecological considerations for space colonies' found that 'such colonies would present extremely difficult biological and ecological problems (which) should be addressed at the very outset if any serious effort towards designing satellites or colonies on celestial bodies other than the earth is to proceed.' A meeting at the Woods Hole biological station in Massachusetts pointed out that the biological problems which are likely to arise should avoid being 'considered

engineering problems rather than basic humanistic and biological ones.'

The biologists point out that the O'Neill plan involves building 'a new meta-stable ecosystem, complete with biotic resources and closed cycles for other essential resources, and capable of supporting man over long periods,' and that 'No such system has ever been built on Earth.' They add that 'the probability that such a system can be built and maintained indefinitely at present seems remote . . . especially when we realise that we have no background in the analysis of the problem and no technical or scientific research programmes under way at present to develop the background.' Although work is being done on the mass driver idea, and although there has been substantial biology done on man and other organisms in orbit, space colony biology is an unknown.

Among the questions raised at the Woods Hole meeting and later is whether the six key biological elements – carbon, hydrogen, nitrogen, phosphorus, sulphur and oxygen – which biological systems need in bulk, and the many others needed in smaller quantities, could be cycled round the colony – delivered and removed – in the right quantities, sometimes as gases, as required by living systems. There will also be problems of seasonality. Most plants and animals are used to annual variations in temperature and rainfall. Energy input, without the Earth's atmosphere to regulate it, will also need controlling. So will water supply – the meeting participants pointed to the need for 'something similar to a coastal system, with both terrestrial and aquatic components.' All these problems, as well as considerations like the minimum land area and volume of space required, need to be solved, as well as the ability of the final life-support system to support the people who would inhabit the colony. The problems need to be solved in order; first on Earth, where mistakes are less permanent and then in space. 'Only after successful self-contained systems have proved feasible on Earth for some time ought such systems be launched.' But it is obvious from the biologists' statement that some of them are itching to get at the knotty scientific problems conjured up by O'Neill's ideas.

That may seem like enough ecological problems for any space programme. But according to Dr David Thompson, a biologist who has spent time looking at man's impact on the Antarctic and who is now taking a close interest in the analogies between man's exploitations of space and the Antarctic, it is only one aspect of a wider 'astropollution' problem. This could ultimately threaten the solar system with as big a man-made impact as most areas of the Earth have already received. Early examples of man's impact on space include the temporary lunar atmosphere – consisting of gases vented from manned spacecraft – which have already been detected during Apollo missions. Thompson wrote, again in the *Co Evolution Quarterly*, that 'If the Moon ever supports a sizeable population or regular spacecraft traffic, the "induced atmosphere" might become dense enough to interfere with some uses of the Moon, such as its use as a base for astronomical observations.' This puts Thompson in mind of Project West Ford, a plan to put 350 million short copper hairs into Earth orbits as a reflector for US military radio links. (They could have been used for other radio traffic as well.) The scheme ended in failure but could, according to the International Astronomical Union, have caused great interference with radio astronomy. There was also an American military scheme to launch a large geosynchronous mirror into space to light up South-East Asia during the Vietnam War – an artificial Moon to eliminate night, which would also have eliminated astronomy.

According to Thompson, space near Earth is already filled with tens of thousands of pieces of junk, most of which will not go away in any reasonable period of time – there is no rust in space and no biology. What he wants is for us to look on space as a place where man's activities have an effect, not an infinite sink from which nothing placed there ever emerges again. The lesson to be learnt is the one man has already taken on board about the oceans and is learning gradually about the Antarctic. Examples of 'astropollution' already abound. Solar cells of space satellites were damaged by the explosion of a 1.4 megaton nuclear weapon test carried out in the upper atmosphere above the Pacific in 1962. And every manned spaceflight

seems to observe the 'firefly effect', an unwanted convoy of paint flecks, sewage, hydraulic fluids, nuts and bolts, and other paraphernalia accompanying it through space. So far, as Thompson points out, the sheer cost of doing things in space has not made people do them in more economical ways that they do nearer home. In the same way, there is, he says, massive waste at Antarctic research stations despite high transport costs. The Cuban cow killed by bits of a falling US rocket in 1961 may be just the start, so that the insurance industry (Lloyd's of London is already heavily involved in insuring satellites) may find a new business area in cover against unplanned re-entries. Thompson is worried about, for instance, the temporary but severe effects which rocket launches have already caused in the Earth's upper atmosphere. But he seems to be rendered speechless by the even larger scale plans for exploiting the solar system devised by, amongst others, O'Neill and his Princeton colleague Freeman Dyson. Dyson is a Professor at Princeton's Institute for Advance Study, the academic home of Albert Einstein for many years. Dyson has proposed that the rate of expansion of man's place in the Universe will eventually be limited only by the speed of light, as people spread through the galaxy with the 1960s concern about a possible clash between population growth and natural resources long forgotten. One is reminded of one science fiction novel, author and title long forgotten, in which archaeologists argue furiously about which planet man might have originated from, and of course get the answer wrong.

Dyson takes a radical view of space as an engineering proposition, in a way which would terrify Thompson. Thus he was one of the first to propose what is now called 'terraforming', altering the processes at work on the inner planets of the solar system so that man can live on them. Dyson disregards the fact that Venus is only about the same size as Earth and Mars is a good deal smaller, so that the total area available there is not a dramatic improvement on Earth. (In his book *Disturbing the Universe*, Dyson also produces calculations to show that it could be cheaper for man to homestead the asteroids than it was for the Mayflower settlers to move to America, or for the

Mormons to decamp to Utah.) Dyson proposes (the idea originated with science fiction writer Isaac Asimov) that the obvious way to get some use out of Mars is to introduce water there. He proposes doing this by means of sending a self-reproducing automaton to Encladus, a satellite of Saturn which seems to consist at least in part of ice. In Dyson's thought experiment, many tiny sailboats are used to get the ice to Mars, making a constant rain of watery meteors: eventually rain falls and oceans form. The payoff from the one automaton sent to Encladus is virtually infinite.

Dyson thinks that eventually civilisations based on planets will decide that their suns are simply going to waste by putting the huge majority of their energy into space. He also thinks that inhabitants of O'Neill space colonies will come, unless everyone is very careful, to resemble the inhabitants of *Brave New World*. So he has made 'some rough engineering designs of the machinery required to take apart a planet the size of the Earth and reassemble it into a collection of habitable balloons orbiting around the Sun.' Dyson thinks that the Earth itself is too precious to chew up in this manner, but there are lots of dead planets to use instead if you cast the net wide enough. And if you want to make complete use of the energy output of a star, his least modest proposal so far is the 'Dyson sphere', a thin sphere of material made by getting a large planet (Jupiter would do fine) and redistributing it as a sphere around a star. 'The construction of an artificial biosphere completely utilising the light of a star is definitely within the capabilities of any long-lived technological species.'

How would this project place mankind in the Universe's civilisation league? Dyson points out that it would only get us on to the second level of the three-stage grouping of civilisations proposed by the Soviet astronomer Kardashev. Type 1 civilisations control the resources of a whole planet (we are only approaching that level now, so that man is still off the bottom of the Kardeshev league.) Type 2 controls the resources of a star. With the UK-type 1 per cent compound growth per annum, Dyson reckons that will take another 2500 years But even he thinks that level 3 is a way beyond that. It requires effective interstellar travel

since a level 3 civilisation controls an entire galaxy. But once there, it is hard to envisage any catastrophe wiping out a type 3 species: it would be too thinly spread. For this reason, mankind is likely to come across type 2 or 3 civilisations rather than across type 1 ones. In addition, species at stage 2 or 3 will stay there longer than type 1 species do, and have more noticeable astronomical effects. For instance, a Dyson sphere would take in visible light from its central star and give it out in infra-red wavelengths, since the sphere would be a lot cooler than the star within. So the infrared astronomers should be the first to spot a Dyson sphere, unless its inhabitants are very noisy in radio wavelengths.

Of course, the Kardashev classification assumes that technology is a measure of civilisation; not morality, music or even science. It also assumes that civilisation starts on planets, which it perfectly well may not. But if you like the long view, it is something for mankind to think about if it is ever tempted to think it has run out of worthwhile goals.

3 Satellite Communications

1945 was a crucial year in Man's postwar rush into space. It was the year in which the Second World War ended and the USA and the USSR took over Germany's rocket experiments, making them the solid foundation for their own military and civilian space efforts. But some space experts regard 1945 as crucial for quite another reason. It was the year in which a British engineering magazine, *Wireless World*, published an idea which more than anything except its potential for war – has made space a national priority for the world's major powers. The article was by a 28 year old electrical engineer, Arthur C. Clarke, and the idea was an inspiration.

What Clarke had realised, in one of the great scientific insights of the century, was that a satellite could be placed by rocket in an orbit round the Earth directly above its equator, and that if it was at a distance of some 35,700 km above the equator, orbiting in the same direction as the Earth's rotation, it would do an orbit of the Earth once a day, and so appear completely stationary to an observer on the Earth's surface. Three satellites in what are now called 'geosynchronous' orbits – at 120 intervals around the Earth's equator – would allow transmissions to be relayed to and from virtually any point on the Earth's surface. Hence the title of Clarke's paper, *Extraterrestrial Relays*. Clarke has often lamented that he would now be very rich if he had patented the geosynchronous satellite idea before publishing it, although his later exploits as a writer of science fiction and fact may have made him the world's most highly rewarded author. And over the last 20 years, geosynchronous space – in other words, all points 35,700 km above the Earth's equator – has become so much in demand that international regulation has been proposed to ration it out between different agencies competing for it. As

well as 'extraterrestrial relays', weather and other satellites have been put there to take advantage of the unique properties of the only place where a satellite can seem to hang stationary in the sky.

But it is communications satellites which are the main users of geosynchronous space. Even the USSR, which mostly lies a long way North of the Equator, began launching geosynchronous communications satellites in 1975 when its Statsionar series began. And communications is the main civilian use for satellites, well ahead of meteorology, science and other uses. The reason for this is a vast increase in the volume of international telecommunications traffic, mainly in the form of telephone calls, which it is important to look at before we can get an idea of the potential for communications satellites.

Telephone calls have become dramatically cheaper since the Second World War as they have dropped in price, in real terms, and as people have come to have the money to afford them. As well as increased affluence, international telephoning has been encouraged by the rise of multinational corporations – even when calls are cheap, it hurts less if someone else is picking up the bill – and by the way in which technology has made it simpler to make international telephone calls. In 1979, the British Post Office claimed that 80 per cent of its telephone subscribers were able to dial calls direct to over 80 overseas countries. The result is that growth rates for international telephoning have often exceeded 20 per cent per year, and for more exotic services like computer data transmission or telex, a telephone like teletype system, have been known to reach 100 per cent per annum.

Not all this growth has been taken up by satellite communications. International undersea cables, for instance, are still being laid at a rapid rate and by 1983, a UK-US-French consortium expects to have completed the seventh transatlantic cable. That cable will cost over £100 million ($200 million) and provide 4000 transatlantic phone links, a cost of over £25,000 a channel. By comparison, an Intelsat V satellite, a type due to be coming on stream in the early 1980s, will cost some £2800 per channel. Cables have advantages for some uses over

satellites: the lines have less interference and communication is virtually instantaneous, which means that a computer bureau user in London, for instance, can use a computer in Toronto as easily as one next door via a cable link. If he were using a satellite link, there would be a noticeable delay before the computer replied to his questions. But for most uses, satellites seem bound to be the main beneficiaries of the growth in international telecommunications, because they are cheaper than the existing options and more flexible, a rare combination.

The paradox is that, although satellites are cheap and can provide advanced communications facilities easily, the countries in the best position to take advantage of them are probably not the rich Western nations with a huge amount of capital already invested in telecommunications systems, usually groaning under the huge amount of traffic they are now being called upon to carry. Instead, the countries which may be more likely to enter the next century with modern communications systems are those in the Middle East, for instance which are starting virtually afresh. In April 1979, that consideration brought dozens of American and European corporations to Bahrein for a Middle East communications exhibition in the hope of getting on board huge potential telecommunications markets there. Among the proposals were two from a European consortium and the US Hughes Aircraft Group for a satellite system, Arabsat, to provide the whole of the Middle East with sophisticated telecommunications services including radio and television as well as telephone and telex calls and computer data. All these firms are looking for a stake in a world telecommunications market worth about £15 billion ($30.4 billion) in 1977: by 1987 it could be £33 billion ($65.3 billion). This number of dollars, although huge, and growing at an average of 7.9 per cent over the 1977 – 1987 decade, conceals the fact that, because of advancing technology, the power of the equipment installed will be growing even more rapidly.

Thus the Intelsat satellite system, which is responsible for most of the world's satellite communications, is expected in the 1979 – 1983 period to see the amount of traffic it carries to grow by over 100 per cent. The Atlantic

Ocean region will, Intelsat thinks, exhibit the fastest growth – 114 per cent over the five years – but the Indian Ocean and Pacific regions will nearly double their traffic levels, growing by 98 per cent and 91 per cent respectively. The Intelsat system carried about 60 per cent of the world's transoceanic telecommunications traffic, according to Intelsat evidence to the US House of Representatives, with cables across the Atlantic and Pacific carrying most of the rest. It seems likely that the Intelsat system and other satellite communications systems – at which we shall take a closer look soon – will succeed in getting the bulk of the new market for long-haul international trunk calls and other international telecommunications traffic. That will mean a vast improvement in the quantity and quality of international communications, and at a lower real cost (Between 1965 and 1979, Intelsat's charge for a single space communications link fell from $32,000 per year to $5760.) But it will not bring about a vast change in the sort of telecommunications facilities we have. Other advances in satellite telecommunications both compete with the Intelsat system and could soon add much more sophisticated telecommunications options to it.

The Intelsat system is the biggest civilian satellite communication system of any. It is bigger than the rest put together and likely to remain so. It was set up in 1964 by 11 countries, mostly advanced industrial nations like the USA and Western European countries, and has grown rapidly to the point where it had 103 member countries in 1979, a total achieved in August of that year when Cuba joined in. Cuba's first transmission, aptly enough in view of the high politics which is coming to surround satellites and space, was live TV coverage of the conference of non-aligned nations in Havana.

Intelsat's first satellite, the object of world curiosity when it was launched in 1965, was known universally as Early Bird. Even Intelsat professionals quickly forgot its formal title, Intelsat I, although all its successors have been known by the blander names of Intelsat II to V, the current model. Like many of its successors, Early Bird long outlived its design life, lasting for nearly four years instead of the expected one and a half. The life expectancy of

COMMUNICATIONS SATELLITES: SIZE AND POWER

Type	*Intelsat I*	*Intelsat II*	*Intelsat III*	*Intelsat IV*	*Intelsat IVa*	*Intelsat V*
first launch	1965	1967	1968	1971	1975	1979
mass (kg in orbit)	38	86	152	700	790	967
power (watts)	40	75	120	400	500	1200
capacity (phone circuits)	240	240	1200	4000	6000	12000
design life (years)	1 5	3	5	7	7	7

The Intelsats have evolved in ess than twenty years from 0 59 m high satel..tes which had to interrupt telephone traffic to transm t telev s on to 16 m high vehicles providing 12 000 telephone circuits plus two TV channels The Intelsat VI sate lites, plus b g d rect broadcast TV sate lites and other new commun cat.ons sate lites expected in service th s decade, will continue the trend Between Intelsat I and V, the mass of satellite in orbit per te.ephone channel has ha ved from 0 16 kg to 0 08 kg, leaving as de the nnovation of independent TV capacity.

spacecraft has a lot in common with that of people in the Middle Ages: satellite launches are very risky, as birth and early childhood was then. If that trauma can be got over, satellites tend to outlive their design lives much as people then often had long lives. Early Bird was a small satellite, weighing only 38 kg and carrying just 240 telephone circuits; if a single television transmission was required, no telephone traffic could be carried at the same time. Early Bird was placed above the telecommunications-crowded North Atlantic, and could interconnect only one station on each side of the Atlantic.

Early Bird was the successor of various experiments carried out by NASA, American Telephone and Telegraph, and other bodies, in the early 1960s, which proved the viability of the satellite communications idea. These included Echo, a 30 m diameter aluminised balloon which passively reflected radio signals beamed at it, launched in 1960, and the first two active telecommunications satellites, Telstar and Syncom, launched in 1962 and 1964. Telstar and Syncom were launched by AT&T and NASA respectively, and were the first active telecommunications satellites, containing amplifiers to strengthen the signal instead of just reflecting it back to Earth. Syncom was also the first geosynchronous satellite. Apart from allowing the satellite to be in continuous view, providing non-stop communications, the advent of geosynchronous satellites meant that ground stations could be built without the need for complex equipment to follow satellites in rapid traverses across the sky, making the Earthly end of things vastly simpler.

Since 1965, the Intelsat system has grown to include a total of eight satellites offering a total of 40,000 circuits to countries all over the world. The Intelsat II satellites were no larger than Early Bird, although they were more advanced. Four were launched, of which one failed to enter orbit; of the other three, all launched in 1967, one was placed over the Atlantic and two over the Pacific. These were the precursors to no fewer than eight Intelsat III satellites launched between 1968 and 1970, of which five entered orbit, three over the Atlantic and one each over the Indian and Pacific Oceans. The Intelsat IIIs weighed 151 kg

in orbit, after shedding all the launch equipment, and had a capacity of up to 1500 telephone circuits or four TV channels It was then decided to change over from from the McDonnell Douglas Delta launcher, which had provided the lift from Early Bird onwards, to Atlas Centaur launchers for the Intelsat IV satellites and their successors. All the Intelsat satellites so far have been launched by NASA, in return for a fee from Intelsat

The 14 Intelsat IV and IVa satellites launched between 1971 and 1978, of which two failed to enter orbit, were launched into position 6 over the Atlantic Ocean, four over the Indian and two over the Pacific – by the General Dynamics Atlas Centaur launcher. Late in 1978, five were being kept in reserve, indicating that Intelsat was building up fat for the future. Another was leased out long-term, so that about six Intelsat IV satellites comprised the Intelsat system as such.

The Intelsat system which now exists consists of six Intelsat IV satellites in use, as well as the spares. Of the six, three are the smaller Intelsat IV satellites launched between 1971 and 1975 and the other two are the Intelsat IVa type launched from 1975 to 1978. The difference between the two types is pretty complete: the IVa type is heavier 1481 to 730 kg - larger - 6 8 m to 5.3 m and, most importantly, much more powerful. The Intelsat IVa satellites can carry 6000 telephone channels - 2000 more than the Intelsat IVs – as well as two television channels and are equipped with SPADE, a new system for keeping a number of satellite communications frequencies in reserve instead of permanently assigned to a particular use, which allows better use of the capacity. The first Intelsat IVa, launched in 1976, was built by the Hughes Aircraft Company for £12 million ($23 million) and NASA's bill for the launch was as much again.

The Intelsat satellites are used in conjunction with ground facilities in 88 countries, as at the end of 1977. These countries house 163 ground stations, equipped with a total of 201 antennae. In 1965, there were just five antennae in five countries, so that growth has been precipitous. Even between 1976 and 1977, the number of ground stations increased from 157 to 201. 49 of the

antennae in use at the end of 1977 were being used for domestic telecommunications traffic, using leased capacity on board Intelsat satellites, a business which Intelsat expects to see increase as the simplicity of satellites for communications within countries - especially large ones - becomes increasingly attractive to communications authorities.

The ground stations transmit at 6 gigahertz, six thousand million cycles a second, in other words in the microwave band, which is unaffected by the Earth's atmosphere. The Intelsat IV satellites are each equipped with two sets of two antennas, which look over the portion of the Earth's surface visible from the satellite, and which receive the microwaves and retransmit them, after amplification, at 4 gigahertz. This means that the ground stations can transmit and receive signals to and from the same satellite without confusion.

At the moment, the Intelsat satellites are simply giant amplifiers in the sky. The time seems far in the future when they might also, in effect, be switchboards and telephone exchanges in the sky as well. The receiving antenna collects signals from a wide area of the Earth beneath it at 6 gigahertz, amplifies them with a travelling-wave amplifier, in which an electromagnetic field interacts with the signal and gives up some of its energy to the signal, and are converted to 6 gigahertz waves. These are then sent through another travelling wave amplifier before being retransmitted. With the Intelsat IVa and V satellites, the transmissions to and from the ground can be effectively doubled by using two 'channels' to transmit, with the same wavelength but opposite polarisation. With this technique, the electromagnetic fields of the two channels being received include one clockwise and one anticlockwise, so that the electronics can unscramble them.

Most of the technology in the Intelsat system is on the ground rather than in orbit. For instance, the ground station antennae must point very precisely at the satellite, so that they are almost constantly making very slight adjustments in position. Because of factors like the irregular shape and gravitational field of the Earth, even geostationary satellites seem to move slightly. And because

the satellite has only a small antenna it is up to the ground station to point at it very precisely. Until the mid-1970s, Intelsat insisted that all the ground stations in its systems should have 30 m antennae to allow highly precise signal direction. Now smaller antennae – down to about 10 m – are also allowed, although signals to them must be specially handled, so that Intelsat's fees are higher.

The other problem about the Earth-space link is that the signal must go only to the right satellite. Intelsat now leaves a space of about 2500 km between a pair of satellites over, say, the Atlantic. Geostationary space is so scarce that this may not always be possible, which is why ideas for making use of quiet periods during telephone calls or using pairs of oppositely polarised signals are gaining ground. As it is, the signal is amplified forty thousand billion billion billion billion times as it enters the ground station, is amplified and transmitted to the satellite, amplified and transmitted back to the Earth, and then amplified yet again after reception on the Earth. (The figure comes from Burton I. Edelson in February 1977's *Scientific American*.) Another way of getting more transmissions is to use higher frequencies. The Intelsat V satellites will use a 14 gigahertz ground to satellite band and an 11 gigahertz satellite to ground waveband. The Intelsat Vs will also have the present four and six gigahertz wavebands and will use the twin-polarisation technique as well as very precise ways of using the wavebands completely, allowing them to operate 12,000 calls at once.

All these devices will be hard put to bear the growth of international traffic which Intelsat's members – post offices and telephone companies all over the world – are experiencing. Ford Aerospace, Intelsat's prime contractor, had taken orders for eight of the powerful Intelsat V satellites by the end of 1979 – the last one for £19 million ($38 million) – so that investment by Intelsat is going on quickly, the more so if ground stations, operating costs, and launch costs are all counted in. But the eighth Intelsat V, at $38 million, is cheaper per circuit than the Intelsat IVa satellites at about $24 million a throw, especially when inflation is allowed for. The space sector of the eight-satellite Intelsat V system will cost about $470 million, half

each for the satellites and the launches, according to evidence given to the US President and Congress by Comsat, the US end of the Intelsat system

Intelsat expects demand on its system to double in the five years between 1979 and 1983 This rate of growth would not match the 25 per cent growth seen in 1979 but would still be highly acceptable. The problem is that forecast growth rates for telecommunications are constantly being exceeded.

Europe, the USSR, Japan, Indonesia and others are now mounting communications satellite efforts which may, in time, displace Intelsat from its position as the world's dominant power in satellite communications. Their efforts all lean heavily upon what Intelsat has already done, but they plan to improve upon Intelsat with plans whose political consequences involve attempts to break free of Intelsat, which is inevitably dominated by the USA.

The reason for this US domination is partly technological. US firms build the Intelsat satellites, although there are important non-US subcontractors like British Aerospace in Bristol, England. British Aerospace has supplied a number of important systems for Intelsat satellites, including solar energy collecting panels to power them and microcomputers to control their operations.

But the main reason why Intelsat is generally seen as US-dominated is its corporate structure, by which the different member nations' share in Intelsat is a proportion of the use they make of the system. This means that the USA is, and will continue to be, the biggest shareholder. At the end of 1978, the USA had, via Comsat, just over 25 per cent of Intelsat. The only other country with over 10 per cent was the United Kingdon, with nearly 11 per cent. Germany, France, Brazil and Japan were the only other countries with over 3 per cent. The rest was spread among 96 other territories. So the voting rights in Intelsat are firmly dominated by the USA, especially if political issues arise involving confrontation between the developed nations and the third world. The western developed nations between them have an even more overwhelming proportion of the Intelsat votes.

This means that developed countries decide the

priorities for Intelsat and decide how the system will be developed in space. Thus they have the choice of what satellites will be acquired and where they will go, although it is Intelsat's job to consult its member bodies – telephone companies and authorities, and in some case national governments – about their traffic forecasts and seek tc match them This system seems to have worked well so far. But in future it may be that Intelsat will become more politically contentious, even though it may choose to defuse anti-US feeling by spreading its orders more thoroughly around developed countries' manufacturing facilities. Non-US launchers may also be used to get the satellites into orbit – the first four Intelsat Vs will be launched by US Atlas Centaur rockets and after that the space Shuttle may be used, but there is also the possibility of using the European launcher. Other non-US launchers may be on the way.

The Intelsat system was managed from its inception in 1962 until the end of 1978, by Comsat, its US member, and although Intelsat continues to use Comsat as a provider of technical services, it now has its own personnel in charge. That is important politically despite Comsat's dominant share of the votes. Comsat is seen as closely tied to the US government. Although it is a US corporation quoted on the New York Stock Exchange, it is allowed to operate by an act of the US Congress. The President of the USA can nominate up to three members of the Comsat Board, and receives an annual report from Comsat on its activities. And its activities are overseen by the US Federal Communications Commission. So pressure can be expected for Comsat's role in Intelsat to be reduced even further, although it is already being reduced from within by US government intervention. Because of US competition policy, Comsat is probably the only Intelsat member without a monopoly on Intelsat ground stations in its own territory American Telephone and Telegraph, RCA, ITT and other US telecommunications firms also have a share in the stations, although Comsat runs them. AT&T uses them for carrying its communications traffic within the USA.

The problem from Comsat's point of view is that

although transoceanic telephone calls, and other long distance telecommunications, are growing fast they are not particularly good business. So Comsat is getting into other sorts of satellite communications and other space activities which can tell us a lot about the way satellite communications are going. Comsat's reasons for being restless about what is now its main line of business, transoceanic phone calls, are simple. Rates are governed by US regulatory bodies — mainly the Federal Communications Commission — and so are profits. And as the capital investment in satellite communications gets lower, because of the falling price of electronics and of spaceflight, the regulators will be reluctant to see the Intelsat-related part of Comsat make more money.

For that reason, Comsat has gone into remote sensing by buying ERT, a firm providing environmental data to companies and governments. This is part of an attempt by Comsat to set up a commercial body to sell satellite remote sensing data, more about that in the chapter 'Looking Back' in this book. Comsat is also looking at the possibility of going into providing satellite TV broadcasts by subscription direct to homes and offices in the USA. There could be data and text transmissions as well as normal TV programmes, provided subscribers had the right sort of TV sets. The technology exists, according to Dr Joseph V. Charyk, President of Comsat; but the scheme depends on the idea's commercial viability, which in turn involves the messy political question of how the USA's telecommunications, and those of the rest of the world, are going to look at the end of the century.

Another satellite communications idea being explored by Comsat involves marine communications, where a marine version of Intelsat called Inmarsat has been set up to sell improved communication systems to the world's merchant navies. Initial talks on setting up Inmarsat were held in late 1979, although Comsat General, a Comsat subsidiary, had held tests since 1976 with three Inmarsat satellites. These were used in tests with over 175 ships, each with a small mast-mounted antenna, and three shore stations. Although the first three Inmarsats are expected to last well into the 1980s, it is also possible that Inmarsat will

use the European Space Agency's Marecs satellite, developed for ship communications, which should be in action in the early 1980s, or will use leased maritime communication capacity on Intelsat V satellites. Traditionally, ships have had little information available to them except by a single radio channel, and a system capable – as Inmarsat is - of offering high quality data transmission, involving telex, computer data and facsimile as well as speech, could change marine practice almost as much as satellite navigation is already doing.

In addition, Comsat General is involved in two ventures of much wider potential, impinging on the whole of communications politics (Inmarsat, although it is dominated by Comsat much as Intelsat is, also includes the USSR and the People's Republic of China. The USSR does not belong to Intelsat although China does.) These developments, both involving new satellites, are called SBS – Satellite Business Systems Inc – and Comstar, and both are meant for internal use in the USA.

SBA – set up by Comsat General along with computer giant IBM and Aetna Life Insurance – is the initiative which has other communications setups like AT&T worried. In late 1980, SBS said that it expects to be offering electronic mail services to US firms by 1980, with a system presumably compatible to Intelsat's fledgling Intelpost service, which is undergoing trials at the time of writing. This sort of service – providing almost instantaneous transmission of mail with virtually the same quality as the original – is worrying post offices worldwide, even those which, as in the United Kingdom, also happen to have the telecommunications monopoly. IBM is the dominant partner in SBS and data processing, including access to sophisticated data networks, is a key part of what it intends SBS to offer, in addition to inter-company telephone communications and other business communications. Hughes Aircraft Company built the SBS satellites in 1979 and 1980.

The point about these services is that they can provide sophisticated services cheaper than land lines, which are operated in the USA by AT&T. Seeing the danger, AT&T is also going into the business. So far it has used rented

space on Comsat General's Comstar satellites – there are three of them – for internal communications, as does GTE, another US communications giant. The point is that AT&T wants to go into the wider business of supplying direct communications - business and domestic - to rooftop aerials, as does SBS. At the moment (late 1979) the Federal Communications Commission has allowed AT&T to leave its present line of business and start offering direct line services to business customers. What remains to be seen is how the US market will work out once SBS and AT&T are both offering services along with two other competitors, Western Union with its Westar satellites and RCA with its Satcom satellites. Both had been overwhelmed with demand from TV programme distributors and others, tempting other US high technology firms like Texas Instruments to contemplate entering the field as well.

These firms are both planning large telecommunications systems of a sort which only satellites can make worthwhile. If landlines are the main telecommunications medium – and that includes modern developments like fibre optics as well as traditional copper cables - then AT&T's position, with thousands of miles of cables and thousands of telephone exchanges in place - would be impregnable. Now RCA and Western Union have put three satellites in orbit, with RCA's Satcom III able to carry 24 TV programmes, 24,000 telephone channels, or a combination of the two. Westar III, Western Union's third satellite, is much smaller – 12 TV channels, 7200 telephone channels, or a combination. Both of these systems are the precursors of much larger possible systems which could grow up in the 1980s. RCA has asked for FCC permission to launch Satcom IV in 1981, although the growing shortage of geosynchronous space above the equator to the South of the USA may mean that large Shuttle-launched communications platforms may be used increasingly in the future instead of the proliferation of small satellites made essential by today's launcher technology.

At the moment, these US firms are not heavily involved in communications services for individual corporations. They expect that to become big business in the 1980s.

There, AT&T has the advantage that its landlines can be used as backup to the satellite system it plans to acquire. Business areas of interest to the US satellite communications competitors at the moment include television programmes, where RCA has already had great success in selling a service for transmitting TV shows on a broadcast basis to US TV stations. In July 1979, RCA offered to give a £25,000 ($50,000) receiver for its system to any of the USA's TV stations that would come into the system – there are over 700 stations and about a third of them accepted rapidly. RCA reckons that it can deliver a one-hour programme to 20 local stations from New York for £550 ($1100); AT&T would charge £4000 ($8000) via its landlines.

Another area is news distribution, where the *Wall Street Journal*, which is printed in seven locations around the USA, already uses the Westar system to transmit its pages around the USA. It is the USA's only really national newspaper. United Press International, one of the world's main news-gathering agencies, started a trial in 1979 which will probably lead to all UPI's news services within the USA being delivered by satellite, involving 1000 newspapers, magazines and radio and TV stations. Each subscriber would have a 2 m diameter antenna to receive UPI's coverage. The cost of the receiving system could be less than £2500 ($5000) per receiver once the system is going on a large scale.

This sort of system is considerably easier to arrange than a business communications complex for a large corporation, where very large amounts of information will be produced from many different offices and must be delivered to the right destination. Here, capital costs on the ground will be higher – SBS is talking about £125,000 ($250,000) terminals with a monthly rental of say £5000 ($10,000). But for that, customers will, SBS intends, get access to a system capable of moving 6.3 million bits of information per second. As the *Economist* of London put it, that is equivalent to a lorryload of documents per half hour, taken from and delivered to as many different addresses as the customer wants. Files and books could be moved as well as letters, and television conferences could

be held, avoiding travel. Internal telephone services and computer services would also be available, and no doubt SBS's main shareholder, IBM, would be willing to furnish suitable computers.

If the politics of US regulation and satellite communications seems complex, the international aspects are even messier. Broadcasting is comparatively cheap - even the poorest third world countries have a radio station, to allow overseas countries to be plied with propaganda and, often more importantly, to allow governments to keep their hands on a vital machine for internal political control. The radio station is always a primary target for planners of *coups d'état*. Traditionally, the main international radio powers have been Western nations as well as the USSR and the People's Republic of China. If third world countries are to be able to transmit more international radio – and more and more of them want to – it seems that the rest of the world will have to sacrifice at least some of the wavelengths it now uses. The growth of satellite communications, and the communications revolution it promises, complicates the picture even more, since satellite communications frequencies are now probably as hot a property as airspace in the traditional broadcast bands, mainly the short wave. The danger for the third world is that US corporations will grab all the airspace for business communications. That fear was one of the factors behind a massive conference held in 1979 to thrash out the future of the airwaves.

The rather unpromising title of the Geneva conference was WARC 79, the World Administrative Radio Conference, which conveys little of the flavour of one of the decade's most vital international political meetings. The Third World's objective was to overthrow the 'first come, first served' approach to satellite wavelengths which has so far been observed, and which arguably served well when the USA was the only country producing communications satellites on any scale, with the US military and the US-dominated Intelsat as the main communications satellite users. A previous WARC, devoted entirely to satellite communications and held in 1971, resolved that countries have equal rights to both geostationary space and the wavelengths necessary to use it. The fact that

wavelengths have been registered with the International Telecommunications Union for use in satellite communications – mainly, in practice, by the USA – should not mean that they cannot be reassigned to other nations by the ITU. But between the 1971 and 1979 WARCs, no plan was set up for changing the 'first come, first served' system. In 1974, the USA entered an objection when a similar motion was passed at a WARC on maritime communications. At a 1977 WARC on broadcasting satellites, a similar resolution was passed again, but this time the USA succeeded in having it limited to Africa, Europe and Soviet Asia, resisting a scheme to extend it to North and South America.

WARC 79 was concerned with terrestrial space and radio communications. The US stance was that allocating frequencies would give rise to inefficiencies – countries would claim air space they did not need, just in case they might eventually use them, the allocations would get out of date, and ambitious satellite schemes would be frozen into current technology. None of this was very convincing to delegates from the Third World, or to officials from Europe, Japan and other areas of the developed world with their own satellite plans. But as with previous WARCs, the results were ambiguous and the future of satellite broadcasting frequencies and the ITU, which would run any allocation system for them, remains misty.

1900 people meeting for 10 weeks at WARC 79 had had the battle lines drawn for them in advance by a group of Third World countries, pressing for a 'fair shares for all system' like the one for broadcasting satellites resolved upon by the 1971 WARC. That position is one which the USA would find hard to accept, although if it is given as few teeth as the 1971 decision there could be little in it to harm US plans. The most extreme position – put forward by Colombia and nine other countries through which the equator happens to pass – is that geostationary space should be the property of the nation vertically below it. (You will remember that satellites can only be placed in geostationary orbits, some 37,000 kilometres high, in positions above the equator.) That position would mean that ten countries could put geostationary satellites into

orbit over their own territory and the others would have a choice between using geostationary space above the oceans or, presumably, paying a fee to one of the 'group of ten'.

Developed nations other than the USA went to WARC 79 looking for the same thing as the Third World - more satellite communications space, or at least the guarantee that it would be available for them if they eventually need it. The Third World came armed with the accusation that countries like the United Kingdom keep airspace they do not need for imaginary uses, and that their radio stations often use more than one frequency for the same transmission for no technical reason. In the end, no strong regime was set up at WARC 79 to ensure the freedom of the airwaves, and future political battles along the same lines seem certain. However, some of the technologists at WARC suggested that if countries gave up frequencies they did not need, the position would be considerably eased, especially if technologies akin to those now in use in the computer industry – and espionage – for compressing data, and thus shortening messages, were used. These could include 'packet radio' and 'packet TV' systems, developed out of 'packet switching' computer data transmission systems, which could in principle quadruple the amount of use made of the UHF part of the radio spectrum, and other wavebands.

The most ambitious satellite communications plans outside the USA are those of the European Space Agency and, of course, of the USSR. As well as pan-European efforts co-ordinated by ESA, there are numerous national and international efforts involving European countries, and countries like Australia, Canada, Japan and Indonesia. It is even easier to see the dominant effect of space communications in ESA's programmes than in those of the US National Aeronautics and Space Administration, because ESA is much smaller and because it lacks NASA's strong military involvement. Communications satellites are one of the three main strands of ESA's programmes' applications, along with science and remote sensing.

ESA's satellite communications ambitions centre around ECS, the European Communications Satellite. This is a scheme to provide Europe and other possible

customers with a satellite communications system for the 1980s, and possibly beyond, as good as anything US efforts can provide. So far, ESA has concentrated upon developing a satellite which can provide communications for areas like Europe and perhaps the Middle East, the Far East or Japan It is the eventual ambition of European firms, many of which already supply parts of spacecraft to Intelsat, to become suppliers of sophisticated switchboard-in-the-sky type satellites some time this century, for use either by Intelsat or other operators. But at the time of writing, ESA's main communications satellite efforts are directed towards its prototype Orbital Test Satellite, OTS.

The OTS programme got off to a bad start in September 1977 when OTS-1 was destroyed during launch from Cape Canaveral. Its Delta launcher exploded under it. OTS-2 was launched successfully the following May. It was placed in a geostationary orbit directly South of the European mainland, above the Gabon. From there it was able to communicate with points from Iceland and the Canaries across the whole of Europe and North Africa. OTS was judged a success, not just by ESA but by the telecommunications authorities which joined in the experiment and which expect to become users of ECS when it is in position.

For ESA's first try, OTS is a large satellite; it weighs nearly half a tonne and has four communications channels, giving a total of 7200 telephone circuits, or eight TV channels. The main purpose of OTS was to allow the different parties involved to get experience of communications satellites for the main business they now perform – telephone calls, TV coverage of major events, and the like This has happened at least as well as ESA hoped, according to the European telecommunications authorities' organisation.

For the OTS experiment, the European telecommunications authorities formed an interim Eutelsat organisation, whose membership includes the main potential users of the European telecommunications satellite series. At first, OTS was used mainly with ESA's own ground station in Italy and with a French post office ground station near

Paris. Later it was also used to communicate with ground stations belonging to other authorities in Germany, the UK, and elsewhere in Europe and North Africa – TV traffic was carried regularly on OTS from Europe to Cairo and to Rabat in Morocco, and in 1979, when OTS has been in orbit for a year, the French Ministry of Posts and Telecommunications was using it as a regular link for TV transmissions between France and French-speaking North Africa.

OTS also demonstrated a range of less conventional telecommunications possibilities which geostationary satellites open up and which had previously been confined mainly to military users or to small-scale experiments. For instance, OTS was able to receive and transmit TV signals, as well as telephone traffic, via small transportable antenna, in a successful series of experiments which were not in the original OTS plans. OTS was also used to set up an international scientific data network based on the Rutherford Laboratory in the UK, the European Centre for Nuclear Research, CERN, in Switzerland, and other high energy physics centres in Europe. In addition, ESA and other establishments like Britain's Royal Aircraft Establishment used OTS for electronic document distribution, computer data exchange, and for holding conferences with the participants in touch by television. Like the TV experiment, these used 3–14 m antennae, the smaller ones being movable.

When OTS was launched in 1978, its expected life was five years. It seemed set at the end of 1979 to outlive that, so that it may well still be in service until the full ECS is operating. The experiments carried out in the first 18 months of OTS's life were so encouraging for ESA and Eutelsat, the customers, that by September 1979, no fewer than five ECSs have been ordered, the biggest ever satellite procurement in Europe and the first communications satellite programme outside the USA and the USSR on such a major scale.

The ECSs will be built by Mesh, a consortium of aerospace firms in the UK, France, West Germany, Sweden, Italy, Holland and Spain. ECS looks like being a cheaper satellite than the new Intelsat V-series – the three

ordered in September 1979 had a price of only just over £12 million ($24 million) each. ECS will be larger than OTS 12,000 telephone channels and two TV repeaters, to be used within the European Broadcasting Union's system, which at present distributes TV coverage to European TV stations by landlines and microwave links.

A contract signed in May 1979 between ESA and Eutelsat – whose 17 member nations include all 10 ESA members – gives the outline of how ECS will work out in operation. The first ECS will be launched if all goes well late in 1981 – although delays are as much a part of satellite communications as any other high technology enterprise. A second will follow ten months later for use as a backup, and the pair will be placed in orbits above the Gabon The other three satellites – £37 million worth, plus about as much for launchers – will not be needed for some time, barring disaster with the first two. The design life of the ECSs is seven years and the existing contract between ESA and Eutelsat runs for 10 years, so that at least the third ECS may be needed during the life of that contract. The fact that ESA feels the need for three backups shows that uncertainty is still an important factor in calculations about satellite communications and other space ventures. The plan is for all the ECSs to be launched from the ESA test range in French Guiana with Ariane, ESA's own rocket, providing the push. Money has been earmarked for all five Arianes, but by late 1983, the end of the first 14-rocket launcher programme for Ariane, it may be that cheap costings for Space Shuttle launches from the USA will have made Ariane seem a lot less attractive, despite the history of delays and cost increases being experienced on the Shuttle in 1979 and 1980.

ECS will provide European countries with telephone, telex, TV and data communications services via a series of 15 m antennae, which the members of Eutelsat will buy and run in the same way as they do Intelsat ground stations. The one-satellite system will not supplant existing land lines and microwave links within Europe, but should provide low-cost telecommunications even though most of the main areas in Europe originating telecommunications traffic – in the UK, West Germany, the Low Countries and

Northern France - are very close together.

At the moment, ESA has no telecommunications plans comparable to those of SBS and other groups in the USA. The intention is to provide a regional version of the Intelsat system, which could have export possibilities to other areas, such as the Middle East. But ECS is not the European Space Agency's only scheme. It also plans to launch a marine communications satellite, Marecs, late in 1980 - before ECS - with others in 1981 and 1982. Marecs, which is being built by the same Mesh consortium as the main ECS, closely resembles ECS. ESA hopes that it will be used by Inmarsat, the Intelsat-type body set up to offer satellite communications to civilian shipping. The Inmarsat system could eventually consist of four geo-stationary satellites offering 50 telephone circuits each connecting ships to shore stations. According to Mark Hewish in the *New Scientist* (15 November 1979) 'the nine European countries participating in Inmarsat own 36 per cent of the world's shipping. At present only 7 per cent of ships' messages are transmitted by radio telephones, the rest are sent in morse code and it can take 12 hours for a high-frequency morse link to pass information. This will be reduced to a few minutes with Marecs.' Marecs will also be able to transmit weather bulletins, safety information and distress calls.

In the longer term, ESA also has plans to go into aircraft communications - it is carrying out a study jointly with Comsat General for the International Civil Aviation Organisation on a possible Aerosat project which could involve worldwide satellite systems for air traffic control.

But the first ESA satellite to be launched by Ariane - NASA put up OTS - should have been none of these. In May 1980 ESA's unsuccessful second Ariane launch carried along with Firewheel, a science satellite, Amsat, a ham radio and communications satellite. Amsat was to be the ninth ham satellite - the USA and the USSR have both launched predecessors - and was equipped with a micro-computer to allow it to act as a switching centre for home computer owners in Europe and elsewhere. Like previous amateur radio satellites, it was to act as well as a message centre for radio amateurs. Most radio amateurs

live in Northern latitudes, and Amsat was to be in a polar orbit whose highest point is above the North Pole, making it spend most of its time above the Northern Hemisphere.

Most European countries' satellite communications efforts are concentrated on ESA's programmes. But there are exceptions among the major ESA members British Aerospace, for instance, which is the lead contractor in the Mesh consortium, announced in September 1979 that it was carrying out a study for Radio Luxembourg, a radio station transmitting over most of Europe, which could lead to a direct-broadcasting system to carry TV and radio coverage direct to homes all over Europe. The cost would be dramatically less than using an array of land transmitters to do the same thing. The reaction to the idea from established radio and TV organisations – Sir Charles Curran, formerly Director-General of the British Broadcasting Corporation, was aghast – was one of horror, although the problem of equipping every customer with a dish aerial on his roof - it could be up to 3 m in size - would be much more formidable than that of establishing the space end of the link.

France - the European country with the biggest commitment to space projects – and Germany are also active in satellite TV projects. They have set up a consortium to develop a direct broadcast system called TV-Sat, which could be in operation by 1982 or 1983. Again, 1 m antennae would be needed on roofs to receive TV-Sat's output. ESA's L-Sat is a direct rival to TV-Sat The announcement of the TV-Sat project caused concern to ESA, which would like to be the only European space authority, although France and West Germany have agreed that Ariane will be used for the launches. The French also plan to launch two of their own Telecom 1 telecommunications satellites in 1982 and 1983.

The USA and Europe are both developing satellite systems with one eye on their own needs and the other on communications possibilities worldwide. The third great power in space, the USSR, looks at the problem in a different way, being mainly concerned with securing communications links within the USSR. The USSR looks

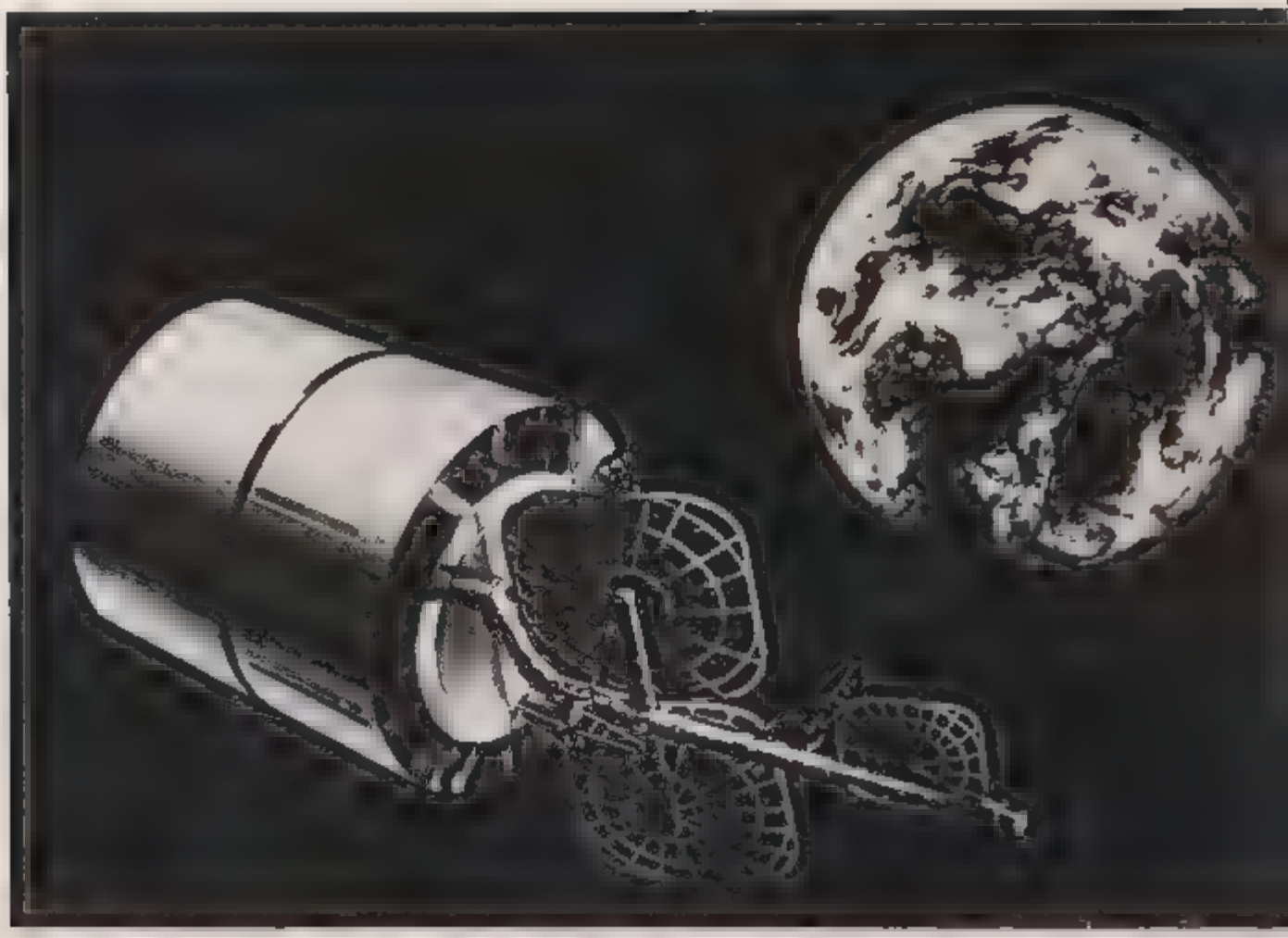
upon satellite communications not as an addition to a well-established telecommunications system, as Europe and the USA must, but as a means of building a satisfactory telecommunications system where none now exists.

The main series of civilian satellites in use by the Soviet Union at the moment is the Molinya group, of which four types had been launched up to the mid 1970s. They were the precursors of the Statsionar series of geostationary satellites which the USSR is now beginning to deploy. The first three Molinya types were all placed in very eccentric orbits so that – like Amsat – they spend most of their time above the Northern Hemisphere, providing maximum coverage of Soviet territory. Over 60 Molinya 1, 2 and 3 satellites had been launched at the time of writing, between them providing good telecommunications coverage of the USSR and adjoining areas. They also provide communications links with manned Soviet spaceflights as well as weather photographs and other services. In orbits about 400-500 km high over the Southern Hemisphere and about 40,000 above Russia itself, the Molinya satellites are designed to be used with a series of 33 ground stations – called Orbita – in the USSR, and one each in Cuba and Mongolia, according to Reginald Turnill in his *Spaceflight Directory*.

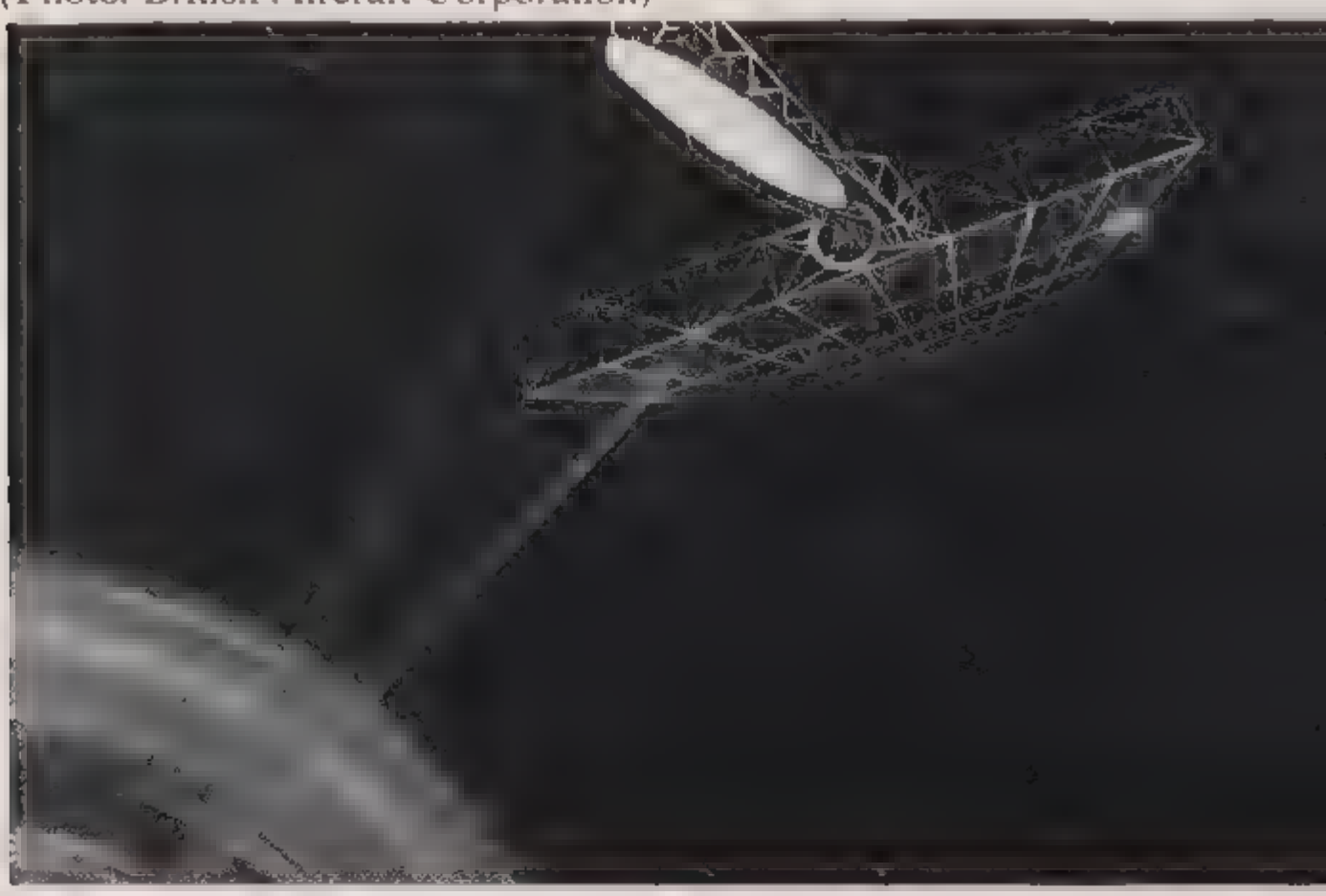
The Molinya satellites grew from well under a tonne in weight at first to about 1.5 tonnes with the later Molinya 3s. The system they provide, although not having the advantages of geostationary operation – fully steerable ground stations are needed to follow the satellites across the sky – do provide coverage of even the most northerly parts of the USSR, which is a problem for geosynchronous satellites which must be placed above the equator. The Molinya system allows quite complete coverage of the USSR with at least three satellites, running round the same orbit eight hours apart. Molinya satellites were used almost entirely for intra-USSR communications, although there were also communications with Cuba, Mongolia and France. Franco-USSR co-operation also included French satellites launched jointly with Molinyas and Moscow-Paris TV transmissions. The Molinya satellites were also used to replace landlines in providing the Moscow-

Prototype Space Shuttle Orbiter preparing to land at Edwards Air Force Base California The real thing will re enter the Earth's atmosphere at 25 imes the speed of sound and be landed without power, unlike normal aircraft
Photo Rockwell International)

NASA's space telescope, due to be launched in 1983 or 1984 It will be able to take a much longer, clearer look into space than ground based telescopes operating at the base of the Earth s atmosphere
Photo: Lockheed)

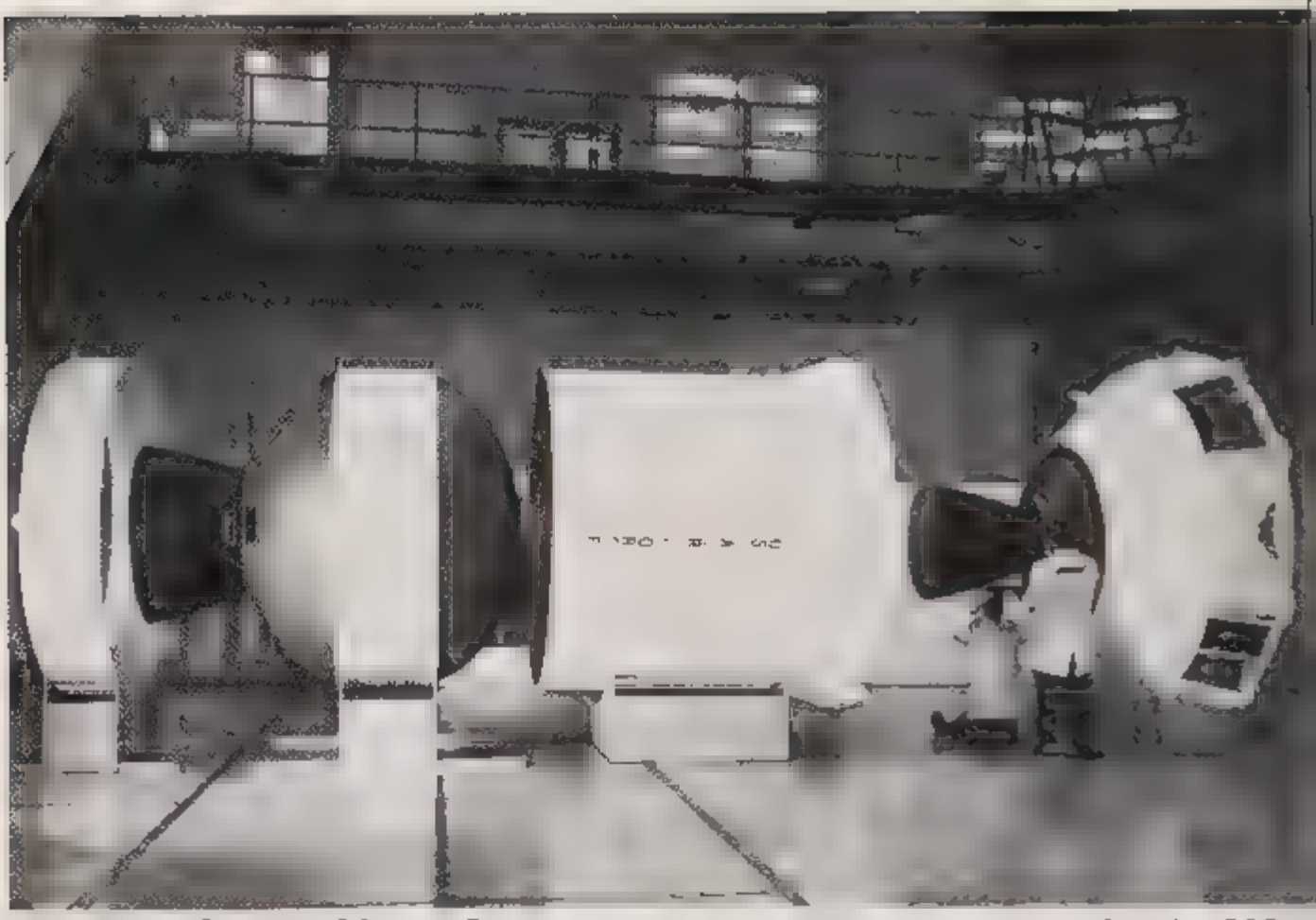


This Intelsat communications satellite is one of a group strung around the Earth's equator and used by the 100 plus member nation Intelsat organisation for carrying a majority of the world's fast growing telephone, TV and other telecommunications traffic
(Photo: British Aircraft Corporation)



The Solar Power Satellite would be the most massive engineering project ever 115 square kilometres of very high technology; nearly 36,000 kilometres from home
(Photo: Boeing)

The central area of a Solar Power Satellite — look for the Shuttle Orbiter for scale
Photo: Boeing)



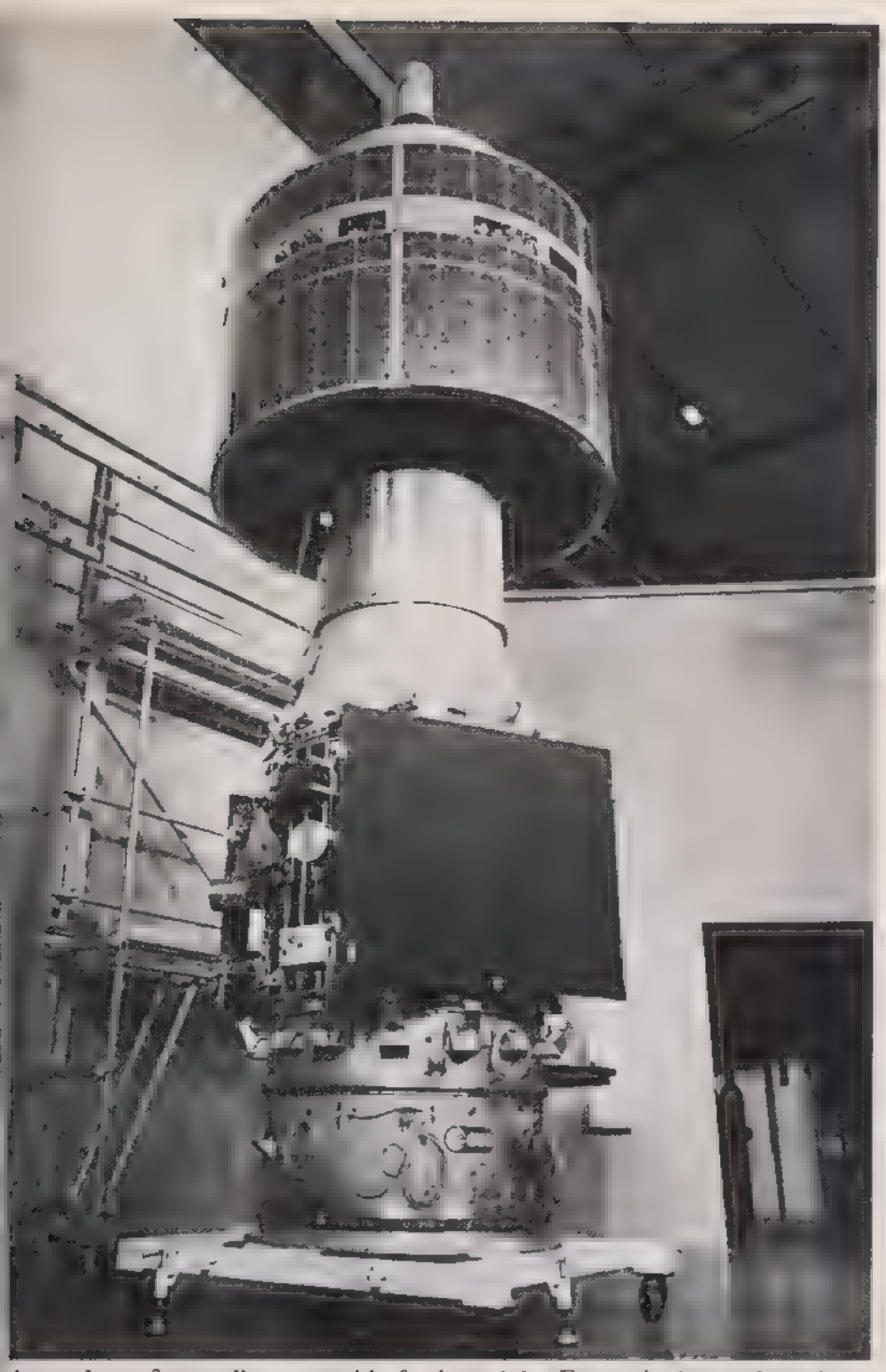
This is the Inertial Upper Stage, a two-part vehicle being built for the US Air Force to carry payloads from the low-level orbits accessible from the Space Shuttle to the high orbits, including geosynchronous ones, required for many space missions
(Photo: Boeing)

An artist's impression of the European Earth Resources Satellite The satellite system will provide new data from the sea surfaces of the Earth.
(Photo: British Aerospace)

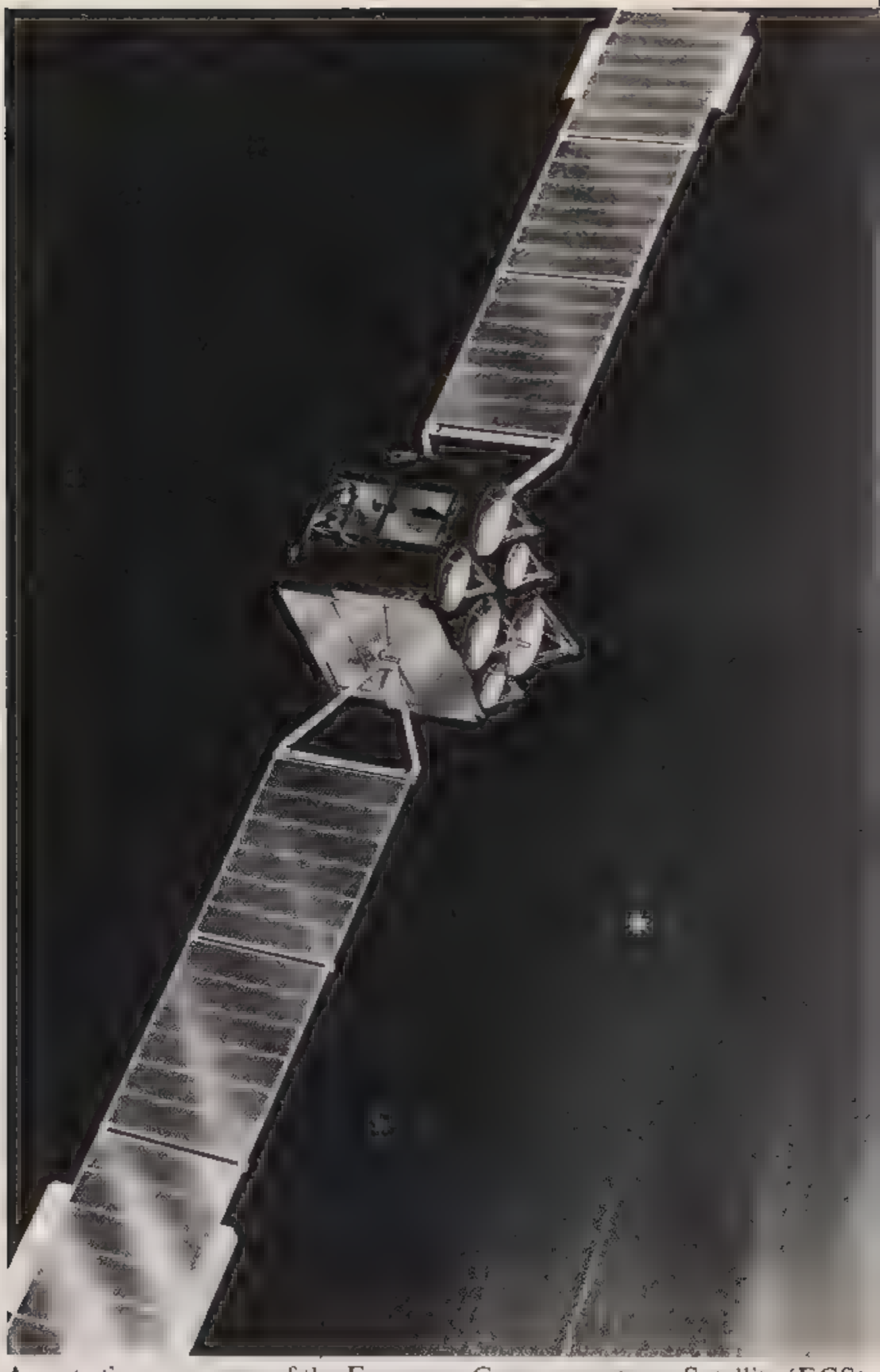
This British Aerospace Skylark rocket is one of many hundreds launched by many research organisations in Europe and elsewhere. Early work on space astronomy and zero gravity material processing has been carried out with them, as well as research in the upper stratosphere

Photo: British Aerospace Dynamics Group, Space and Communications Division)

One of the many demanding tests carried out on satellites before launch. Testing the moment of inertia of the European Space Agency's Orbital Test Satellite.
(Photo British Aerospace Dynamics Group, Space and Communications Division)



A mockup of a satellite assembly for launch by Europe's Ariane launcher from top to bottom, Deteostat 2, a meteorological satellite, Apple, an Indian Satellite, and CAT, an instrument package
(Photo: European Space Agency)



An artist's impression of the European Communications Satellite (ECS) one of the growing number of communications satellite systems designed to provide a communications service to particular regions of the world. (Photo. British Aerospace Dynamics Group, Space and Communications Division)

Washington hot line, for use in political emergencies, along with Intelsat.

The geostationary follow-up to Molinya, Statsionar, is designed to put the USSR into the same league as Intelsat. The problem from the Soviet point of view is that Intelsat is well established and there is little room for a rival except among the few nations under direct Soviet influence. The first two geostationary satellites to be launched by the USSR were Cosmos 637 and Molinya 1S in 1974, and Statsionar 1 followed in 1975, much delayed. The rest of the Statsionar system is designed to use up to six satellites to provide Intelsat-type world coverage from positions over the Atlantic, Pacific and Indian Oceans. But it may be that these major developments will take a back seat in Soviet planners' minds because of the apparent success of the first three Molinyas, which have been used to transmit radio and TV programmes to the Soviet Union itself. There is also the political problem that Intelsat and Molinya satellites are or are planned to be close together over the oceans and use the same 4–6 gigahertz wavebands. So there is a potential problem of interference. Some of this will be alleviated by the Intelsat V satellites' use of the 11–14 gigahertz waveband, which is already used by ESA's communications satellites.

Late in 1979, there were five Statsionars in orbit, two being spares, and they were in use mainly to provide TV and radio coverage for the Soviet Union itself. According to Major General William R. Yost, the US Air Force's space systems and communications director, they also had a potential for providing secure military communications in the 7–8 gigahertz waveband. According to Yost, the ultimate aim of the Statsionar programme may be to lure countries away from the Intelsat system. This would be hard to do. The Intelsat system has over 100 member countries in it even Cuba, home of a Molinya earth station. There is little to be gained by leaving it in favour of a rival network with only a few member countries, even if the price is lower. Another possibility could be a merger of the two systems once the USSR has enough Statsionars in orbit to put herself in a position of strength.

Yost also told the US Armed Forces Communications

and Electronics Association of a number of Soviet communications satellite schemes at an earlier stage of development than Statsionar – which, to add to the confusion, is sometimes also known as Raduga. The most advanced, with four satellites in orbit at the end of 1979, is called Ekran, meaning screen, and is a geostationary TV satellite. It is used to carry TV to the Soviet Far East and to Soviet ships at sea, both civilian and military. Another, with two satellites launched by the end of 1979, is Gorizont, or horizon, and is another TV satellite, launched to provide coverage of the 1980 Olympics in Moscow. After that they will probably be used to provide new civilian and military communications capacity, being capable of operating in the military and civilian wavebands.

In the longer term, the evidence is that the USSR plans several new types of communications satellite. The information which is available about them is not lavish – it is only known at all because the Soviets are obliged to tell the International Telecommunications Union in advance about wavelengths in which it intends to operate. It seems that in terms of civilian satellites, the USSR plans a new seven-satellite aeronautical and maritime satellite system called Volna – wave – whose relationship to Inmarsat is not clear. Presumably Volna will also be used for military purposes. Another system, called Luch, meaning beam, will be a domestic and international system in the 11–14 gigahertz waveband, which it will share with Intelsat V, ECS and SBS.

In the longer term, the logic which is propelling the USA towards very large space-assembled communications platforms – see below – must clearly apply to the USSR as well, especially if, as is reported, the Russians are developing a re-usable space plane like the Shuttle.

Satellite communications figure in most of the space programmes of smaller nations – only remote sensing is anything like as popular in national and international space ventures – and non-superpower space programmes are interesting because they show a fresh approach to the benefits which space technology can bring, for instance, to poor, large countries with many isolated communities. Without satellites, they might never have a hope of building

up national telecommunications systems at a sensible cost. With satellites they can. A prime example is the Canadian Arctic, where the Anik system has been in action for some years, bringing telecommunications, especially television, to areas where isolation had previously been a way of life.

The Anik programme began in 1972 with Anik 1, followed up by Anik 2 and 3 in 1973 and 1975. These satellites, part of whose capacity was leased to US authorities to provide communications to Alaska, had a capacity of 960 telephone conversations or a colour TV transmission each. They were used in exciting experiments in carrying educational and other TV programmes to the Canadian Arctic. The English, French and Eskimo languages were all used (Anik is Eskimo for brother). All three were judged a success by Ottawa, as were the small portable ground stations they served. Their successors, the Anik D satellite series, will start to be launched early in 1982, and will each have a capacity of two TV channels or 1820 telephone conversations, twice the size of Aniks 1 to 3. The Anik Ds will be built by a Canadian firm, Spar Aerospace, which acted as a subcontractor for the earlier Aniks, and they will be launched by the Space Shuttle unlike previous Aniks which were put into orbit by Thor-Delta launchers. By 1982, Anik 1 will be nearing the end of its useful life, and the first Anik D will be used in the beginning to replace it. It is a reasonable surmise that the Soviet authorities looked closely at the Canadian experience with Anik a series of geostationary satellites which were used successfully to transmit to the Arctic when considering their own geostationary satellite programme, now under way.

Two much more experimental satellite communications programmes – both being carried out with non-American launchers and home-grown technology are those of Japan and China. It has been suggested that China and Japan's space programmes may now begin to converge as a result of China's increased international presence. Japan's communications satellite plans so far have all been experimental, starting with CS1, a medium capacity experimental satellite launched in December 1977 to test the technology for launching and operating a Japanese

communications satellite, and its ground stations. It was launched with the Japanese N-1 launcher from the Tanegashima Space Centre and controlled from the Tsukuba Space Centre, although Japan has plans to acquire an international network of ground stations. It would also seem sensible for the Japanese at least to consider a launch site nearer the equator if it plans to launch geostationary satellites, since the amount of energy needed to put a satellite into a geostationary position increases rapidly with latitude, reducing the effective payload.

The next CS series launches planned are CS 2A and 2B, scheduled – in mid-1979 – for 1982 and 1983 with Japan's N2 booster. These are planned for telephone and other point-to-point communications, and there are also plans for a broadcast satellite, BS, and for communications with ships and aircraft. And there is a series called the Experimental Communications Satellite, ECS. This is no relation to the European Communications Satellite, another ECS. The Japanese ECS programme got off to a poor start in February 1978 with a launch failure.

The Chinese are proceeding in a rather different manner from Japan, developing a system which has many points in common with European communications satellite plans. A 1980 launch seemed, late in 1979, to be planned for the first Chinese communications satellite, using a 200 tonne rocket based on the CSS-X4 intercontinental ballistic missile which the Chinese have developed for military use. The plans seem to involve two geosynchronous satellites to provide cover of China itself as well as the Pacific area, Europe and Africa. The satellites are called STW, which is an abbreviation of Shiyan Tongxin Weixing, Experimental Communications Satellite, and they may be followed by a broadcast satellite in geosynchronous orbit. The Chinese seem to have been working on STW since the early 1970s, although the system's practicality remains unknown. Late in 1980, the launch had not occurred.

Satellite development plans for the Third World had become so many by the late 1970s that the USA, still firmly the world leader in the field, had become alarmed. At the

major UN conference on science and technology for development held in August 1978, the US delegation came armed with a mass of proposals for US aid to the Third World, covering subjects like food, education, and family planning, under the management of a new US Institute for Scientific and Technological Co-operation The ISTC proposal also involved a major new education and broadcasting satellite scheme, which would cost $24 million over six years to set up.

An example of the sort of scheme which the US proposals may have been designed to short-circuit and which seem certain to go ahead whatever the USA decides to do – is the Indonesian satellite communications system, which links several thousand islands in Indonesia with two satellites almost identical to the Western Union Westar ones. They cost vastly less than cables or microwave towers, even with ground stations included. The success of the Anik programme and of the Indonesian Palapa satellites means that other countries like India have formulated extensive satellite communications plans The first Indian communications satellite – which will also do meteorological work – is due to be launched in 1981 and called Insat-1; it is being built by Ford Aerospace, one of the main US satellite builders. Most of India's satellite efforts seem to be concentrated on remote sensing, with one eye on minerals and the weather and the other on Pakistan's armed forces and nuclear plants. Another Indian communications satellite is due to be launched by the European Space Agency in 1981, assuming that the Ariane programme runs as planned. It will be called Apple, Ariane Passenger Payload Experiment.

The same logic as gave rise to schemes like Anik has also caused Australia, for instance, to plan a satellite communications system which should bring television and telephones for the first time to many parts of the outback. A three-satellite system is planned with the first launch in 1984, and there may be trials with an Intelsat satellite before that. A 1.2 m antenna will be used in the system, like the one used with the Anik satellites, and costing only £200 ($400) each. The total cost should be about £75 million ($150 million) for three satellites one in space to provide

the service, a backup in space, and a backup on the ground plus ground control. Earth stations for major cities would cost just over another £10 million ($20 million) and there could be another £40 million ($80 million) on smaller earth stations for TV stations and other users like the Department of Transport.

One thing which all these schemes imply is that more and more roofs, fields and gardens are going to be decorated by satellite ground stations – the terms ground station and earth station are interchangeable – since an increasing number of satellite communications schemes rely on broadcasting radio, television and business communications of all kinds direct to the recipient. And one essential technological preliminary for all these developments has been to show that small, cheap antennae really can receive low-powered signals from far-off geosynchronous satellites. Nearly 100 countries now have Intelsat receiving stations, which are of two types, A or B. The A type are larger – about 30 m antenna size – and are in general use where traffic is heavy. Large communications groups like the British Post Office operate several of them. The smaller standard B size – about 10 m – was allowed into use by Intelsat later than the standard A size, and Intelsat charges more to countries using it because it can only receive more powerful signals. Despite this, standard B stations are seen by many telecommunications companies as a growth market. In 1979, for instance, the UK firm Plessey formed a subsidiary to supply them, and went into business with two large orders already on the books.

But the big growth in ground stations promises to be in smaller antennae. The Plessey management, for instance, seems to regard Intelsat B stations partly as a way of obtaining knowledge of small satellite antennae in preparation for upcoming developments like Satellite Business Systems. The technology is not complex; the most demanding parts are the amplifiers, which although they must amplify very small signals – millionths of a watt at most received from space – for use in telephone or television systems. Although that sounds a problem, it has been well solved, with a number of available systems, by electronics engineers. The point is that smaller aerials –

made possible by better electronics, higher frequency satellite transmissions, and higher powered satellites – will allow small aerials which could be made of pressed steel, like a car body, to be used at low cost In one contract awarded in 1979, Holiday Inns in the USA awarded manufacturers Scientific-Atlanta with a contract to supply 87 satellite ground stations for TV reception. The cost was not far over $1 million (£500,000) for what is now regarded as quite a large antenna 4 6 m – and the associated electronics. The antennae for, say, the SBS receiving stations may be smaller than that and will probably be cheaper, since the numbers involved will be larger. The same type of antenna will be used for shipboard reception of messages in the Inmarsat system, although the first European shore station for Inmarsat, being built in Rogaland in Norway, will cost about £3 million ($6 million) and be more comparable to an Intelsat B station.

Broadcasting may eventually be as big a market for earth stations as business communications, especially in the USA where there are hundreds of newspapers, TV stations and radio stations potentially in the market for news and programmes by satellite, now sent out expensively by wire or radio links. United Press International, mentioned above, is a prime example, and so are the US public broadcast systems, the non-profit radio and TV networks. In 1978 the General Telecommunications Group, part of the US multinational Rockwell, was given a contract to build all 192 earth stations for a satellite system serving the USA's public radio stations all over the USA including Alaska and Puerto Rico. For a price of $12.9 million (£6 million) the system will include a central transmission point where programmes can be put together and distributed to radio stations; 15 of the 192 receiving points will also be able to transmit. The system, due to have started up early in 1980, will provide several radio channels which can take stereo or quadrophonic broadcasts. The system, using 4.5 m antennae, will take programmes via Westar satellites.

The revamping of the public radio distribution system by GTG follows a similar contract, already completed, to

supply 150 receiver-only TV ground stations for the public broadcast TV system. That was claimed by GTG as the first major use of small terminals for TV satellite distribution in the USA.

Small antennae are thus on the up and up, and so are clever ones. The first satellite antennae had to be steerable – since the satellites were not geosynchronous – and large, since they were weak transmitters. Now antennae can be small and fixed. One idea being looked at by Comsat, which already has a prototype working, is a long, narrow antenna which could observe up to seven geosynchronous satellites at once. Geosynchronous satellites must, after all, be quite close together in the sky, as they are all grouped in a line at a constant distance above the equator, an elongated antenna should, if shaped very precisely for the satellites it must observe and the place where it is to be used, be able to separate out their transmissions at points along a line instead of focussing them on a point as a normal antenna would. Comsat has applied for permission to build three such toroidal antennae in the USA, and each would be able simultaneously to observe three domestic US satellites, Comstar, Westar, and RCA Satcom, which are located near together above the equator to the south of the US mainland. The cost would be over £500,000 ($1.1 million) compared to some £400,000 ($800,000) for a conventional antenna which could look at only one satellite at a time. This is a good deal, potentially, for large corporations and others wanting to be plugged in to a large and varied information flow.

Satellite communications are one of a range of postwar technologies which are transforming communications. The first such development which makes the others possible is solid-state electronics, which began with the transistor – much smaller, tougher, more reliable and less power-hungry than the electronic valve it replaces – and has since gone on to even greater levels of miniaturisation. Now almost invisible microprocessors can carry out more complex or tedious computations than the first warehouse-sized computers. Almost all the modern and future satellites mentioned in this book depend on microprocessors – especially the Western ones – in a number of ways,

especially for controlling and managing them in orbit, where lightness and low power consumption are crucial

In addition to the microprocessor and other computers, satellite communications will, during the remaining part of the twentieth century, probably be integrated with land lines, microwave radio links and fibre optics to provide vast information flows of a scale and immediacy never available before except possibly to the more well-funded security services. Cables, made of copper or other metals, are familiar, and so are radio links which carry an increasing amount of telephone communications in Europe, the USA, and elsewhere. Fibre optics – bundles of plastic threads along which messages can be carried in the form of light beams – are less well-known but have great potential. They promise to carry a greater volume of information than a cable of the same cost or size, because the threads carrying the light can be very fine and the information content of a light beam can be dramatically higher than that of an electric current. Other technologies are much less well-proven, for example the idea, now being tested by IBM, of transmitting information from point to point in the form of infrared light.

How could all these satellites, ground transmission links, computers and microcomputers link up to give new 'Imperial Highways' of information, potentially as important politically as seaborne trade routes? According to the European Space Agency's S. Hannell, a specialist in satellite applications for information systems and other uses, the implications could be dramatic. He points out that experiments in linking science laboratories together – referred to above – by means of ESA's Orbital Test Satellite have shown that whole continents can be spanned by computer data networks. Some computer bureaux, which sell time on large computers to firms which would not find it worthwhile to own them, already operate from continent to continent. In the future, according to Hannell, satellite-based data networks will cease to be a thing for specialist users like particle physics laboratories. Instead, satellite links in connection with data bases of up to date information seem likely to be generally available by the telephone and TV systems within the next decade, taking

over some of the functions of newspapers and specialist magazines.

The advantages of such systems is that they will be instantly updated, they will use much less newsprint and other resources than printed media, and they will be vastly more flexible in use. Anyone with a TV will be able to have access to information files on a vast range of subjects once major data bases have been placed on computers. They will also be able to build up their own files on any subject they want to research without access to specialist libraries. That sort of facility will be in addition to electronic mail services, especially for business users, which are already – because of devices like telecopiers – chipping away at the market for conventional postal services.

In these kinds of development, satellites will play a major role mainly because they can do the same tasks – delivering electronic information – more cheaply than cables. The same logic applies to broadcasting, where direct satellite-to home broadcasts of radio and TV programmes seem likely to become important first in countries like Australia, where the cost of laying cables or building chains of microwave towers would be prohibitive, and then possibly in Europe, as evidenced by the study being carried out by Radio Luxembourg. At the moment satellite signals from communications satellites like the Intelsats are so weak that the British Post Office – for instance – puts a lot of effort into finding places for its earth stations which are free from radio interference. If satellites are to broadcast direct to homes in cities, they will have to broadcast with dramatically higher powers, especially as they will be transmitting to much smaller antennae than the Intelsat A and B types now in use. Trials with antennae down to just over 1 m in size have been a success, although the existing broadcasting authorities insist that direct satellite broadcasts to cities will cause insufferable interference with their own broadcasts.

So the future, it seems, will involve fewer newsboys and postmen – and dramatically fewer trips to cities for meetings, days in the office, and visits to archives – as electronic mail, conferences, newspapers and journals get going. All this is likely to involve dramatically more and

bigger satellites than we now have, and most of them must be in precious and comparatively scarce geosynchronous space, a thin band of sky just over 37,000 km above the equator. What sort of satellites can meet the sort of demands for telecommunications capacity which are going to be created in the coming decades?

The next few years will see the launch of several types of satellites launched by conventional rockets and by the space Shuttle - which have grown out of previous communications satellite experience, especially with the Intelsat series. The Intelsat V satellites will have started to be launched early in 1980, and there will also be more and bigger communications satellites for private satellite communications ventures like the established RCA system But it is in the longer term that things could start to be more interesting. For instance, French scientists with the Aerospatiale company are now on Intelsat's behalf - studying designs for a 40 cm flywheel which could be used instead of batteries to store up the electric power which satellites collect from the sun. Satellites spend half their time with the sun out of view, so that some form of power storage is necessary in addition to the solar panels which collect the power. The trouble is that the batteries tend to end their useful lives after about seven years, which is why that is the limit beyond which existing Intelsats cease to be useful. A flywheel, even one suspended by a magnetic field instead of a set of mechanical bearings, would obviously stop in time, but it could be 14 years, twice the figure achieved with batteries, doubling the useful life of communications satellites and perhaps others.

Another Intelsat research contract, this time awarded to the Hughes Aircraft Company in the USA, could be even more important. It is a step on the way to regular satellite-to-satellite communications, which would mean world-wide satellite communications with satellites doing the work now done by repeater stations on the ground, with the important difference that they would do the work now done by telephone exchanges as well. A frequency band – around 30 gigahertz, far above the 4–6 and 11-14 gigahertz used for satellite-ground communications – has been allocated for satellite to satellite communications, but the

limited use now being made of satellite talking to satellite is military only.

Intelsat now – late in 1979 – thinks that its earlier programme of eight Intelsat V launches will not be enough, mainly because of rapid growth in traffic put through its Indian Ocean satellites, which serve Middle Eastern and African countries as well as parts of South-East Asia. Intelsat may have to build more or bigger satellites, partly because some countries are anxious to lease part of Intelsat's satellites to provide domestic telecommunications. Intelsat expects that by the 1990s it will be using virtually every electronic trick to make the most use of the radio space to which it has access, as well possibly as launching heavier versions of the Intelsat V satellite with more capacity, needing the space Shuttle or the Ariane rocket to put them in place.

It is both new launchers and new communications needs which are making new satellite designs, which a few years ago would have seemed absurdly exotic, become an engineering possibility. Several firms are working on NASA contracts designed to demonstrate the possibilities of large geosynchronous communications satellites. General Dynamic and Convair, for example, are carrying out a £125,000 ($250,000) study for NASA's Marshall Space Flight Center of large space structures capable of supporting several different types of communications antennae. The growing scarcity of parking space in geosynchronous orbit is NASA's main reason for carrying out the study; already the RCA and Westar satellites used to serve North America are very close together and there is going to be more demand for the same small bit of space. It might well be easier as well as cheaper to use the same structure. NASA adds that remote sensing, meteorology and other activities could also be on the same platform, which would be assembled by astronauts working from the space Shuttle.

Such structures could easily be several hundreds of metres across, involving, for instance, an extendable antenna being developed by another US corporation, Martin Marietta, which could be folded down to less than 9 m across and extended – after it had been deployed from

the space Shuttle's cargo hold to its full 200 m size. The antenna would be built of gold-plated wire mesh, mounted on graphite and plastic tubing.

NASA's Office of Space and Terrestrial Applications, OSTA, is leading these sorts of efforts and intends to bring the technologies involved to the stage where they can be taken up by Intelsat and other commercial organisations. NASA will not get into the business of launching and operating communications satellites. What NASA, anticipating growing crowding in the existing wavebands for satellite communications, envisages is a growing use of higher (20–30 gigahertz) frequencies, and possibly of 1 gigahertz frequencies as well The higher frequencies will allow high-speed data communications through even 5 m satellite antennae, which could be launched already assembled by the space Shuttle. The 1 gigahertz waveband would need 30 m antennae in space, a very different prospect involving space construction.

The Shuttle will be able to launch 18 m long satellites with masses of about four tonnes into geostationary orbit – the Intelsat V's weight is just under a tonne and just over 6 m long, so that even without space assembly it will be possible to put much bigger satellites into position. At the moment, the main limit on how large and complex a satellite is put into orbit is weight, and as it becomes possible to orbit heavier and heavier satellites, the tendency will be to put complex equipment there which is now concentrated on the ground, in telephone exchanges and elsewhere. According to Ivan Bekey, head of Advanced Concepts at NASA Headquarters, this opens up possibilities like wrist-radio communications, direct TV by antennae well below 1 m across, electronic mail and other developments which could lead to 'wireless cities' instead of 'wired cities' by the turn of the century.

Bekey described three examples of systems now being looked at by NASA in a 1979 issue of *Astronautics and Aeronautics*, the magazine of the American Institute of Aeronautics and Astronautics. They included personal communications with wrist telephones, electronic mail, and educational TV direct by satellite. The personal wrist radio system is designed to link 10 per cent of the estimated

US population of 250 million at the end of this century, the educational TV system would link all 65,000 schools in the USA, or all the USA's 4000 universities along with 250,000 remote terminals for students. And the electronic mail idea would handle mail – 15 billion items a year of it – between 544,000 terminals in US government buildings and offices. That is about 15 per cent of the mail which the US Post Office expects to be handling in 1990. And Bekey reckons that each of the schemes would work at a sensible cost. He ought to know; before moving to NASA he worked for the Aerospace Corporation on investigating all three ideas.

The wrist radio idea would use a satellite with an antenna at least 70 m across, in the 5 gigahertz radio waveband. The radios could be used for 16 hours of conversation between batteries, and could cost as little as £5 ($10). The point is that the satellite, by recognising a code preceding each message which gives its destination, just as a telephone number does, would route it to the user, whose wrist set could only decode messages for him. The 'switchboard' would use a technology called wafer scale integration to produce a switching system twice as powerful as the biggest Bell switching centre now available but with about a tenth the weight, and power requirement. The whole satellite, including switchgear and antenna, would weigh somewhat over 20 tonnes. According to Bekey, the whole thing would be in operation in 1990 if a start is made in 1980.

The question, of course, is one of costs, and Bekey did the sums including the cost of research and development as well as the equipment involved, and compared to a ground-based telephone system. Complete coverage of the USA except for Alaska and Hawaii cost £1.1 billion ($2.3 billion) in Bekey's final reckoning, compared to costs of £10.4 billion ($20.8 billion) for incomplete coverage of the USA with a similar land-based system. Call costs would be 0.5 US cents per minute with the space system and 5.4 cents with the terrestrial equivalent, which would use radio relay towers to connect users to the existing telephone system. Most of the costs of doing it that way are the telephone companies' fees for providing the lines. The ground system would also lose £200 million ($400 million) a year while the space-based one would generate a profit of £800 million

($1.6 billion) and produce a return on the investment of no less than 70 per cent per annum. Those sort of calculations rarely work out so spectacularly in practice, not least because of lawsuits and government interference, but they ought to make any self respecting capitalist at least pay attention.

The Electronic Mail system would provide a terminal for all US government offices with more than five staff and for all major offices of US corporations with over £500,000 ($1 million) in assets. Those offices are mainly in and around big cities. The antennae needed to pass 15 billion mail items a year between these offices would have to be only 9.5 m across, and each receiving and transmitting station would have a 1 m roof aerial. The terminals in the offices would be like facsimile machines now in commercial use. The satellite would need to weigh only about two tonnes, an easy launch for a single Shuttle or an easy thing to bolt on to a large geosynchronous platform. The terminals could carry from 31 to 2620 typical letters per day.

The lead time for this scheme, according to Bekey, could be even less than for the wrist radio idea, about eight years. And the alternatives, with mail pickups and deliveries or a ground-based electronic mail system using the telephone system, both seem costly by comparison according to Bekey's calculations. It is possible to get the electronic mail costs down with schemes like one being studied by the US Postal Service – where mail is collected and taken to central depots for electronic transmission, but even these would cost about 9.9 cents per letter, against the 15 cents then charged by the USPS An all-ground electronic mail system would cost 25.3 cents per letter and Bekey's system 2.6 cents. The capital costs would be £2 billion ($4 billion) for Bekey's scheme, £12.5 billion ($25 billion) for the ground electronic mail scheme and £10.5 billion ($21 billion) for the USPS hybrid scheme. Of course, only the all-electronic systems would offer virtually instantaneous delivery

Lastly, the educational TV scheme. Using higher frequencies than are now in use – in the 20 30 gigahertz range these would equip schools with 1 m antennae and district buildings with 3 m antennae to transmit the programmes to a five tonne satellite with a 9 m antennae,

which could be folded out after a Shuttle launch. The alternative is to use cables or fibre optics, and these seem to show costs of nearly £1 ($2) per class hour instead of 18p (36c) with the space system. The ground costs are £7 billion ($14 billion) over 20 years as against just over £1.3 billion ($2.7 billion) using a satellite. The cost per school would be less than 5 per cent of a teacher's salary, so that TV could be used as an educational aid almost for free.

4 Looking Back

Looking at the Earth from space, 'remote sensing' to the experts, offers the possibility of measuring such parameters as the thermal capacity of different parts of the Earth's surface. Almost nothing was known about this before the space age. But the most immediately useful ways in which spacecraft can look back at the Earth involve measuring things which have always been of interest to mankind the weather, crops, forests, minerals, and fish for example.

Earth surveillance, the business of looking at all these, began, as do most developments in space, with the military. Spy satellites still account for most of the surveillance of the Earth's surface which takes place, just as most communication satellites are military. The same pattern is repeated throughout the satellite field, which is why the chapter on military uses of space is the longest in this book.

Non-military uses for Earth surveillance are now firmly established, largely as a result of the successful US Landsat Surveillance Satellites, originally known as Earth Resources Technology Satellites. And private entrepreneurs, at least in the case of the United States, are gradually taking over Earth surveillance from government agencies, as they have already done in some parts of the communications satellite industry.

The technology of remote sensing has developed through space exploration. Experience in aerial photography and in using airborne techniques, such as sideways-looking radar, led to the sensors – cameras and other devices – used in remote sensing from space.

Remote sensing uses a wide range of frequencies to gather information about the Earth, its oceans and atmosphere. Visible light is the main frequency; it allows a view of the Earth which can be interpreted comparatively easily, and the Earth's atmosphere is transparent to visible

light. The exceptions are the blue and the violet light colours. These short-wavelength light rays are scattered very easily in the atmosphere and are not particularly useful for observing the Earth's surface – that scattering is what makes the sky blue. But elsewhere in visible light wavelengths, it is possible to take pictures using light of all wavelengths or to choose one well suited to the type of surveillance being carried out. One example mentioned below is crop surveillance, where a wavelength designed to pick up chlorophyll – and hence plant life – is widely used. Infrared light – light with wavelengths just longer than visible red light – is also useful because infrared radiation is equivalent to heat, so that it allows temperature to be 'seen' – of interest to meteorologists, geologists, looking for volcanoes, and of course spies pursuing rocket launches. Radar wavelengths are also useful, radar can see through cloud and vegetation and can be used at night, although it cannot give detail of crops or human activity on the land.

Spacecraft have certain advantages over aircraft in that they can produce, at a low cost per piece of information, a considerable amount of very highly-controlled data showing, for instance, the same land area at the same time of day – in other words with the same illumination by the sun, allowing easy comparison with a different day's data.

The task of getting the technology currently available to make the most of the satellites' potential is far from complete: it is clear that photography is not the only method that can be used. A US National Academy of Sciences working-party on the interaction between remote sensing and the needs of the Third World said that '. . . for various important objectives, especially those related to vegetation, water, geology and mineral exploration, a dynamic range of conventional photographic film is too narrow to gauge parameters such as temperature, magnetism, moisture or chlorophyll content. The combination of new types of sensors with a space platform has proved to be more than a high altitude extension of aerial photography. Remote sensing from space represents a major step forward in the gathering of data about the Earth's resources.' (NAS, *Remote Sensing from Space: Prospects for Developing Countries 1977*).

The sensors aboard Landsat, for instance, include a multi spectral scanner (MSS) and three vidicon cameras, as well as two receivers for data collection and two video tape recorders to hold the data temporarily on Landsat before transmitting it to Earth. The MSS and the vidicon cameras – like earthly TV cameras – operate in seven wave bands in visible light and seven in near-visible infrared light. The wavelengths range from 0.4 to 1.1 mm, millionths of a metre. The trick is to choose wavelengths which allow particular features – such as vegetation – to be seen, and which allow details to be determined by comparing what is seen at different wavelengths. Thus one wavelength is used for penetrating shallow water bodies, another can be used for classifying types of vegetation, and another is best suited to distinguishing between different types of land use.

There does not seem to be much scope for widening the light or infrared wavelengths in use for remote sensing. The promising wavelengths have already been found although microwaves will be used increasingly in the future for radar imaging of the Earth's surface, which can be done irrespective of vegetation, darkness or cloud cover. In addition, the use of large computers to process the enormous amount of data produced by satellites like Landsat will mean that more of the budgets for remote sensing can be spent looking at the Earth and less on the rockets and satellites.

Landsat

More than any other area of space exploration, remote sensing is above all the story of one spacecraft, Landsat Landsat has been a huge success, and can tell us so much about the possibilities for Earth surveillance from space that it is worth looking at it in some detail. Landsats 1, 2 and 3 were launched between 1972 and 1978, with more planned for the 1980s. The first three Landsats weighed nearly 900 kg each nearly a tonne – relatively big spacecraft; they were put into orbit by Thor-Delta rockets. The Landsats were placed in sun-synchronous orbits matched to the Sun's apparent rotation around the Earth. This means that every 18 days the satellite sees the same

part of the Earth's surface with the same illumination by the Sun, allowing direct comparison

Landsat 1 lasted only eight months before a tape-recorder failure, but even so, it had succeeded in photographing all the Earth's main land areas except the Antarctic. After the failure of the tape-recorder it was still able to take pictures of North America and send them live to NASA Earth stations. Landsat 1 was 'retired' in January 1978, having been in use for six years. NASA had originally expected it to last a year and to be replaced by Landsat 2. Instead, the pair were run as a productive team

All Landsat data, even pictures of Soviet launching sites, is unclassified and can be bought cheaply from a centre in Sioux Falls, South Dakota. Most of the users of the data, however, want to look at sea currents, forests, crops, large scale geological structures and other large scale features. Despite this, a ground resolution of less than 100 metres was planned into the Landsat design, and often improved upon. The narrowest things visible in Landsat pictures are long, straight features like freeways in the central USA. The sensors can look at 185 km wide bands of the Earth's surface. The Landsat orbits are Sun synchronous, so that the time on the Earth when the pictures are taken is always about 0930. By that time the Sun is well up, so that little of the landscape is in shadow except in high latitudes in winter, but the angle of illumination is low enough to cast comparatively long shadows. As archaeologists have long known, this makes features stand out more clearly. Soon after Landsat 1, then called ERTS A, was launched, a report was received in Washington which summed up the effect it was already beginning to have on ideas about the interior of Brazil. It said amongst other things that '. . . small villages and towns are located wrongly on the maps by several tens of kilometres; some lagoons which are shown on maps as 20 km long are in reality more than 100 km long; large unsuspected geological structures have been detected.' Not only were the correct locations of towns pinpointed, whole new villages were discovered. The process is reminiscent of the events after systematic aerial photography was first used in the United States, where unmapped towns of some significance were found in the

less developed parts of America. Although the natives were presumably pleased to be noticed by the outside world, they had been getting by for many years without paying any taxes, one aspect of civilisation which gave them little pleasure to catch up with. Another early Landsat enthusiast was Thailand, whose Dr Pladisth Cheosakul, Secretary General of the Thai National Research Council, told NASA that 'the best part of the scenes received (were) excellent' and that '. . . they appear to demonstrate clearly (that) our decision to participate in the ERTS programme from its inception was wise.' In July 1979 Thailand decided to build its own Earth station to receive Landsat pictures. The main use of the station will be to obtain information to monitor Thailand's forests and rice crop, and the Thais will pay NASA $200,000 a year for access to the data, a fraction of what it would cost to collect it from the ground.

In addition, a large number of African nations were early users of Landsat, after pre-launch interest in ERTS from the Organisation of African Unity. In Malawi, ERTS data was used for mapping previously unmapped areas, to help searches for water and to help plan routes for new roads. The success of ERTS 1 was so great that Dr James C. Fletcher, NASA Administrator, said that 'if I had to pick one spacecraft, one spaceage development to save the world, I would pick ERTS.' By that stage – he was speaking at the launch of ERTS 2 in 1975 – more than 40 countries had been involved in the ERTS project and Canada and Brazil had joined the USA in having ground stations to pick up ERTS data.

By 1978 the Landsat 3 was in use, and improvements which had been made after the experience of the first two had allowed the ground resolution to be reduced to 550 metres and other improvements to be made. The improvement has been obtained by using cameras of longer focal length. As with previous Landsats, Landsat 3 has two cameras side by side which give 99 to 99 km square photographs, making a total picture 99 by 183 km. The resolution was also improved by combining some of the spectral bands in which the earlier Landsats had taken pictures. In mid-1979 Landsats 2 and 3 were both

producing good data, despite some camera problems on number 3. It is possible that they will still both be functioning into the early 1980s.

By 1978 Landsat data had become so commercially valuable that the Lockheed Electronics Company had decided to launch a Landsat data centre – in addition to the official US government one – to sell data mainly to large corporations. Profits were expected to be around a million dollars a year to start with and growth rates were anticipated in the 50 to 100 per cent per year bracket for a number of years after operations began. Even before the centre opened, Lockheed was haggling for contracts with three major oil companies to provide them with Landsat imagery to assist in oil and mineral exploration.

Lockheed was also trying to land similar contracts to supply multinational food companies with data for use in predicting crop yields, to assist them in assessing future food market conditions. Other potential customers include a range of government agencies concerned with forestry, agriculture, the environment, transport and the like.

Even before setting up the centre Lockheed had 50 experts at work on data interpretation. The manager of the Lockheed data centre in Houston, Robert E. Tokerud, thought that as well as uses for crop assessment, mineral exploration and other by now familiar applications, Landsat data might eventually find users among large architectural and engineering organisations and in the food industry *after* the crop-assessment stage. Engineers can use Landsat data because they need information about water resources, geology and other Earth conditions, as do mining and oil corporations. And the food industry could use Landsat data for the information they need to plan food processing and transport effectively.

Lockheed's interest in Landsat and its products – a striking piece of diversification for a firm more used to building space hardware than making sense of its output – is relevant to what had, by 1979, become a red-hot issue in Washington's science politics, whether a permanent operational Landsat system should be set up. This could amount to turning Landsat – and with it, the national remote sensing operation – over to private industry in

much the same way as Comsat and other corporations have taken over civilian space communications. In the case of Comsat, this private corporation is quoted on the New York Stock Exchange and has satellites built for it by contractors in the USA and elsewhere. They are launched, for a fee, by NASA. Comsat then operates them on behalf of Intelsat, a consortium of over 100 post offices and other telecommunications authorities. A commercial Landsat arrangement could work in much the same way, if a public authority were in charge or if Comsat were managing it. More details of Intelsat are in the previous chapter.

Although the issue was politically sensitive, President Jimmy Carter was in favour of an operational Landsat system, according to his science adviser Professor Frank Press. And both federal agencies and private firms would also seem to like the idea, which would require Washington legislation to get going. The main question was how? Illinois democrat Adlai Stevenson, one of the enthusiasts for the Operational Landsat idea, launched a bill early in 1979 whereby the system would be part of NASA for at least seven years, after which privately funded bodies could join in. A rival bill launched by Senator Harrison H. Schmidt – a New Mexico republican would set up a private corporation to run the Landsat operation from the outset. Comsat offered to operate the sort of system which Schmidt, a geologist who visited the Moon with Apollo 17 in 1972, was proposing.

Some authorities like Press think that the technology is too young to be handed straight over to private enterprise. He would prefer a more gradual approach involving US government bodies, at least until Landsat D, the latest model, has been launched and more experience gained

So far, Landsat's main users have been governmental rather than private, despite the extremely cheap data it makes available. That pattern of use is a feature which might be expected to change with time. In April 1979 the Intergovernmental Science, Engineering and Technology Advisory Panel found that 35 of the 51 US states had used Landsat data. 18 had used it for land-use analysis, 16 for water resources purposes, and other states for looking at forestry, geology, wildlife and so on. They had spent $17.5

million on Landsat data and trained 1500 people to use it. In addition, seven states had by 1977 acquired independent facilities for analysing Landsat data, with nine others in the process of doing the same. In only 15 states were no specific Landsat activities under way, proving in the Panel's view that the bureaucrats, at least, knew a good thing when they saw it.

To Speed The Plough . . .

The use of spacecraft to look at crops would seem to be one of the most unambiguously beneficial uses for outer space. Even so, only the most credulous will be surprised to find that it began as part of the US espionage effort against the USSR, and that much of the crop-assessment work carried out, at least by the US authorities, is directed to obtaining information about forthcoming Russian crops, although Landsat has also made crop data from space available to many countries, some of which are actively incorporating it into their own information and management systems for food production.

Despite vast achievements since the Revolution of 1917, the USSR has had chronic problems in growing enough food to feed its own citizens. American grain sales to the USSR have been a major fact of life of the governments of both countries for about a decade, and they have also been important to the US commodity corporations which handle the sales. And even when the USSR is not going to be in the market for US or Canadian wheat in large quantities, a knowledge of Russia's food production is essential to American models of the Soviet economy. So picture interpreters at the Central Intelligence Agency and elsewhere in US intelligence are major users of satellite crop pictures.

So far their success has been less than complete. In May of 1978 the General Accounting Office, a congressional watchdog, reported that the USSR's 1975-6 wheat area had been over estimated by about 12 per cent and the yield per hectare under-estimated by 15 per cent. This was on the basis of satellite data. It was just luck that the two errors cancelled out. But there were other problems, like the way

in which the analysts had trouble telling barley from spring wheat especially when the two are at comparable stages of development. The end result of the confusion was that the US Department of Agriculture's plan to set up a world wheat forecasting system was scaled down to a more modest scheme involving an emphasis on drought warnings and other emergency procedures.

Despite this, the Soviets themselves had been stepping up attempts to use their own satellite data to help agriculture. In 1975 they announced that '. . . shepherds in Soviet Central Asia had begun using new pastures according to data collected during observations from outer space.' They were using data collected by Soviet 'Meteor' weather satellites. Millions of rubles were being saved because of the better use of resources and a large-scale experiment was underway to compare satellite and ground observations. The work was being extended as far afield as the Soviet Far East, which is very inaccessible by land, and manned space flights were involved. The crews of Salyut 3 and 4, for example, made a close study of the Mangyshlak peninsula, and hundreds of photographs taken form an essential part of the USSR's 'space atlas'. As long ago as 1976 the Russians were speaking of the prospects for '. . . creating a permanent global environmental control service in orbit' with consequences '. . . for many branches of the economy.'

Despite the General Accounting Office's reluctance, the results of crop assessments based on Landsat seemed to have been generally positive according to the US Department of Agriculture. In 1978 its statisticians carried out an experiment comparing corn and soya bean data from space with traditional land-gathered data and found that information from Landsat 2 data allowed the figures to be improved.

The data used included land areas devoted to different crops, the times of planting, and the progress of the crops as they went through different colour changes, from which their health and maturity could be assessed. In the USA such data is comparatively easy to gather, but the large areas which can be seen in one Landsat picture, as well as the consistent quality of the pictures, means that it was for

the first time possible to get an integrated picture of crops over a wide area without an enormous amount of ground work. In countries with less sophisticated crop information than the USA the improvement offered by Landsat data would be even more significant.

According to NASA, amongst the problems which Landsat data has helped solve for the US Department of Agriculture were how to establish the extent of drought damage to crops around the Volga, including the effects of freezes, hail or storms. In some parts of the USA, one of the main determinants of crop yield is the use of irrigation, which can easily be mapped from satellites, as can the areas of the USSR – the 'new lands' being placed under the plough for the first time.

NASA seems to believe firmly that the sort of problem which bedevilled earlier crop assessment from space, like the wheat barley separation, can be solved by improving systems on the ground or in space. Observations from space cannot be based on, say, the shape of a leaf. NASA points out that colour changes and other large-scale effects have to be there for useful observations to be made from orbit. Thus in the northern part of the Great Plains of the USA, there is an 18 day period when spring wheat is still green and the faster-growing barley is turning yellow. Then it is easy to tell them from each other in Landsat pictures. At other times it is more of a problem.

In the same way the easiest time to tell deciduous trees from coniferous ones is the winter – conifers stay green while deciduous ones lose their leaves. And although it can be difficult to distinguish between corn and soya from space, there is a period of six weeks each season when corn is yellow and soya is still green. Cotton is apparently easy to identify – it has no foliage while everything else around it is likely to be green. This means that a *series* of observations of a widely drawn area, such as Landsat can provide, is needed to build up a picture of what is going on, especially if a number of crops is there.

When initial observations have been made, the problems of forecasting the yields and planning land management can be considered. Forestry has benefited from Landsat for instance. Damage by the gypsy moth - the insect not the

airplane – can be seen, and spraying plans prepared to deal with it. Landsat's spectrometres should also be able to determine biomass (the weight of plant material present) and so give a figure for crop yield, which is now predicted from weather data, historical experience, and other secondary information. The Landsat D satellites of the 1980s will be well suited to this sort of work, having more sensitive spectrometric gear. A five year multi-department study, involving NASA and the US Department of Agriculture, Interior, is now working on the requirements for the next generation of remote-sensing satellites for agriculture.

Striking Oil

Among the first scientists to see the possibilities of satellites for their own research were geologists and geophysicists, who were active in using space photography before the 1970s. Part of the reason for this is that photogeology – geological analysis from aerial photographs – is a well-established and reasonably exact science. With satellites it is possible to do much more, but unlike developments in satellite communications, they use at least a firm base of experience on which geology from space can evolve.

Geologists are primarily concerned to see, from space exploration, an accurate picture of the large and medium-scale structure of the Earth. Most theoretical advances in geology – and virtually all developments of projects such as new oil fields or mines – involve insights about the Earth's structure at a number of levels, particularly involving examinations of the rocks of the Earth's crust in immense detail using microscopes. This is not something which satellites can do much to help. Nor can it directly be of use in the considerable amount of detailed chemical analysis of different rock types, detailed examination of microscopic fossils, measuring how fast oil will flow in a particular sandstone, or finding out the volume and shape of an ore deposit. That sort of investigation accounts for most of the cost of analysing any major mineral resources project. It is worth noting, however, that exploration with geological and geophysical techniques to determine the viability of oil

fields, minerals projects and the like is very cheap compared to the cost of bringing them on to stream. Despite the image of oil and mining industries as great risk-takers, much of the uncertainty has been removed when the geology is done. But the role of satellite imagery in exploration for minerals - including oil and gas - is bound to increase as they get harder to find and as the places where the exploration is done become more and more remote.

One growing exploration area where satellites are of particular benefit is off-shore, which is now the source of an increasing proportion of oil and gas production. Observers are now suggesting that solid minerals will increasingly be mined off-shore, where the role of satellites is vital. In areas like the North Sea oil fields, satellite navigation techniques offer very precise positioning, and this is already displacing established techniques based on radio transmissions from land stations. Geological structures like the rock formations in which oil is trapped are small, so it is important that the platforms which are used to drill for the oil be located within a few meters on the Earth's surface. Land-based navigation systems can sometimes do this, but satellite navigation does it better.

On land the main uses to which geologists can put satellites is to tell them about the large-scale structure of the Earth's surface - in other words to show them views from a few hundred kilometres to a few tens of meters in size. As we have seen this is not enough to enable an observer to determine a red-hot mineral prospect. But it is still very informative, because geologists spend much time worrying about large-scale geological structures. And satellite imagery can save geologists a great deal of leg work, as aerial photography already does. Until comparatively recently exploration companies had not found it worth their while to use satellite pictures simply because not enough were available. That has changed with the availability of Landsat data for large areas of the Earth, which means that the purposes for which it is worthwhile to use an aircraft have been reduced. As time goes on, they should become even rarer. Even if all satellite pictures can do is to isolate a few one-kilometre squares of interest out of a million square kilometres of desert, it is clearly well

worth an exploration firm's time to look at the pictures, especially as they allow a good idea to be formed of the geological setting of the area.

In fact, satellites allow a good deal more to be determined than geological generalities. A paper by R. Cassinis of Milan University as long ago as 1971 outlined the possible effects of remote sensing on the Earth sciences. In particular, large scale geological features like faults, folds and so on can be seen, often more readily than they could by an Earth-bound geologist In addition, dynamic changes on the Earth's surface can be observed easily and quickly, such as volcanoes and landslides The politics of ocean resources has now become so fraught that Pacific countries use surveillance aircraft to look for volcanic islands as they appear, with a view to claiming them as sovereign territory and thus earmarking the surrounding ocean for themselves It cannot be long before the same process is carried out from satellites.

As long ago as 1971, according to Cassinis, photographic work was being carried out on sedimentation on seas and estuaries, and infrared imagery was being obtained of sea currents and freshwater springs in the sea bed. Experiments now regarded as successful were being started on geological mapping again using light-wavelength photography and infrared. Soil can be mapped in the same way, and infrared photography, which is essentially a process for looking at heat output from different parts of the Earth, was being used experimentally to map geothermal and volcanic areas. Volcanoes, of course, are hot and looking at their heat flows is one obvious way of finding out about them. Geothermal areas are essentially regions of low-grade vulcanism where hot water and steam can be recovered from the Earth by drilling. Geothermal energy could make a useful contribution to energy supply in some parts of the world and is already used, for instance, to heat apartment blocks in Paris. In addition, remote sensing from space is being used for wide-area geological surveys and experiments are taking place involving surveying for ores, using light and infrared spectra to obtain chemical data about surface rocks and even for the detection of underground cavities.

At the time Cassinis wrote about these possible Earth science applications of satellites, Landsat was still in the future and many of the ideas had only been tried from high-flying aircraft. Since then geology from space has advanced so much that a number of companies exist which specialise in using satellite photography in oil and mineral exploration. One is Trollinger Geological Associates of Denver, Colorado, whose principal, William V Trollinger, told a conference in London in 1978 that 'our exploration methods of the past are simply inadequate to keep pace with the accelerating demands for petroleum and natural gas', and that what the oil industry needs is advances in large-scale oil and gas exploration to match the progress which has been made in the smaller-scale business of locating oil once promising areas to explore have been located. Trollinger stated that '. . . explorationists originally scoffed at the idea of using aerial photography as an aid, but as the technique became more refined they began to realise the use of three dimensional photography from the air for making surface geologic maps.'

According to Trollinger, '. . . the advent of imaging from orbital satellites has enlarged that perspective even more, giving geologists the potential to systematically analyse the Earth's geologic character on a continental, even world-wide basis.' As an example Trollinger cites a study his firm did of the Peten Basin in Guatemala. What was required was a '. . . regional study of the entire area,' and '. . . the only way to do this was with space photography.' A mosaic of Landsat pictures was used, along with some Skylab photographs, and detailed mapping was produced in stereo showing potential oil-bearing structures. 'The space perspective allows the geologist to make a rather detailed analysis, for the first time, of large structural features of oil-bearing potential. It also allowed a close look at the fault zones which produced a large Guatemalan earthquake in February 1976. In this case not only was satellite geology more practical than the land-based sort, it also allowed deeper and different insights.'

In another case Trollinger's firm did a study of the Idaho Wyoming Thrust Belt, a geological structure in the Western USA. There the terrain is much more accessible

than in Guatemala, but the insight given by Landsat photographs was still valuable. Trollinger says that Landsat provides '. . . an exceptional view of this region, which has been formed geologically in a very complex way. It gives a broad synoptic perspective, which is gained at the expense of detail, proper utilisation of the Landsat data requires support by as much "ground truth" and geological detail as possible.' But the satellite photography allows a revealing look at the geological fault system of the area, which is the main criterion determining where oil may be trapped in the rocks there.

According to Trollinger, the Guatemala and Thrust Belt stories are '. . . but two of many that could be told about Landsat as a useful tool for petroleum and mineral exploration We have shown that it was possible to gain a wealth of important geological information for a minimal expenditure of time and money for conventional surveys through Landsat. Some of the information would have been virtually unobtainable by any other means.' Like other remote sensing enthusiasts, though, Trollinger thinks that they '. . . could have done a much better job if the satellite imagery were tailored to our needs', for instance by providing a higher resolution, more colour and stereo facilities, and sideways-looking radar imagery, which allows large areas to be mapped rapidly even in bad weather.

Trollinger and others have formed a pressure group, the Geosat Committee, 'to evaluate and promote geologically dedicated satellite systems specifically for earth resources exploration.' The committee lobbies NASA and other US bodies, in government and outside it, and although there are no plans for a specifically geology-oriented satellite, there is no doubt that NASA is aware of the potential. Whether Trollinger's aim of getting satellite systems more precisely tuned to geologists' needs will come to be in the short term as hard to assess. But it would appear that even if a fraction of the clever tricks being done in space by military spy satellites were to be used for civilian purposes, most of these wildest dreams could come true overnight. For example, one possibility would be earthquake prediction – spacecraft using lasers to reflect off mirrors located near California's San Andreas Fault give resolutions of

two centimetres, allowing the movement of the fault – and hence the likelihood of an earthquake – to be detected. This kind of experiment is being done world-wide with a US satellite called Lageos.

Weather

One of the claims made by space scientists which is often not believed is that weather forecasts are getting better. In fact they are, even for countries like the United Kingdom which are at the edges of continents and so have weather which is difficult to forecast. Part of the reason is that large sums of money have been spent by meteorologists on some of the world's biggest computers, which are used to analyse weather data. But another critical factor is that these computers are being fed by millions of items per day of weather information from meteorological satellites. From origins in joint Department of Defense NASA projects, the meteorological satellite programme grew to 27 US launches between 1960 and 1970, finally coming under the management of the US National Oceanic Atmospheric Administration.

The NOAA satellites are used in a variety of ways, including international experiments like the 1979 Global Weather Experiment, which involved 140 countries. In 1979, NOAA was planning to launch another eight satellites between June 1979 and 1984 as their predecessors reached the end of their two-year planned life. Built by RCA, the NOAA satellites – placed in Sun-synchronous orbits like Landsat, whose design owes a lot to early meteorological satellites – cost $15 million each, excluding launching, and are thus the most expensive part of a complex system which also involves weather balloons, buoys and aircraft.

NOAA-A, which was launched in June 1979 and started operations properly the following month, was the second of the set of eight NOAA satellites which are to be placed in 830 kilometre-high orbits above the Earth. It will be possible to use the NOAA system to get coverage of every part of the Earth at six-hour intervals; that sort of rapid sampling of the atmosphere is essential for weather forecasting services.

In May 1979, even before the NOAA system was in operation, NOAA reckoned that the USA was saving some $170 million a year. That figure related to the savings from the older Tiros and Goes satellites. (Tiros satellites are in polar orbits and Goes in geostationary ones.) The biggest users of the data were the US Airforce and Coast Guard, which were able to monitor areas of actual and potential bad weather to reduce search and rescue work. That sort of saving is not easy to quantify. Nor are savings of damage to lives and property because of more exact predictions of hurricanes. But there are many direct savings, for instance, fewer aircraft flights need to be made to get weather information. NOAA satellite data have also been used to determine ice cover in the Great Lakes and to forecast temperatures in the Florida area. Temperature forecasts are produced at half-hour intervals, saving fuel which might otherwise have been used unnecessarily to heat citrus groves. Shipping operators can also use weather satellite data to follow ocean currents, saving fuel for ships which can sail with the flow.

Most of the NOAA programme is firmly within the realm of 'applications satellites', the term given to space projects which are designed to be more directly relevant to society than those undertaking strictly scientific research. Despite its success - NOAA pictures are familiar to anyone who watches television weather forecasts - NOAA does not have a monopoly on watching the atmosphere. One of the most interesting such experiments of late was called GARP, Global Atmospheric Research Programme. This pooled together weather data from a vast range of sources, including NOAA satellites and those provided by Japan (GMS, Japan's Geostationary Meteorological Satellite) and Europe (The European Space Agency's Meteosat).

An early exercise - the GARP Atlantic Tropical Experiment - ended in accusations that the experiment has affected crops in Latin America by altering the rainfall patterns. But the 1979 GARP still involves all the 149 World Meteorological Organisation member countries. They received the data (there are no experiments, only observations of existing weather patterns) from receiving stations at Washington, Melbourne and Moscow, and the

amount of information is vast. This is partly because the satellites are not only observing the weather themselves, but relaying measurements from instrumented balloons and buoys. GARP covered mainly the Tropics, between 50 degrees north and 50 degrees south, and it is hoped that the studies on the data will allow more to be found out about the crucial monsoons in Asia and Africa, as well as allowing some work to be done on the polar regions and their effect on weather nearer the equator.

At a still more experimental level is the mapping of the heat content of the Earth itself, which is a crucial ingredient in the weather as well as being useful in studies of environmental pollution, since hot gases and water are worrying pollutants of seas, rivers and the atmosphere. In April 1978 a heat-capacity mapping mission satellite (HCMM) was launched by NASA. Since the satellite's sensors operated in infrared wavelengths – in effect, looking at heat directly – they allowed a direct view of cool areas such as mountains, especially where snow was still on the ground, and also showed up the warm areas around cities. The temperature variations shown by HCMM were mainly at ground level, although some study of cloud cover was also possible. The eventual consequences could be large for pollution monitoring, crop investigations, as well as meteorology.

Other work on the Earth's heat properties has been carried out by American researchers like Thomas A. Croft, who in a fascinating article in the July 1978 *Scientific American* described studies based on pictures of the Earth at night, obtained by the US Airforce's Defense Meteorological Satellites. As well as showing cities and even whole land masses illuminated by moon light, the pictures showed vegetation being burned off on a vast scale by fires in parts of Africa. But the brightest features on the night-time Earth are massive flares of gas being burnt off in the Middle East and Nigeria. Croft calculates that about 4200 cubic kilometres of gas has been burnt off since oil production began in the 19th century. (4200 cubic kilometres of natural gas equals about 10 per cent of proven world reserves of gas at the end of 1977, according to statistics published by British Petroleum.) Fishing fleets

– which fish by lamp light in the Sea of Japan – are also clearly visible. Authorities in Australia, for example, are interested in Croft's work as a way of assessing damage caused by forest fires; it also offers an opportunity of examining whether gas flares might cause damage to the heat balance of the Earth's atmosphere.

At Sea

Most of the effort which has gone into surveillance of the Earth has been directed to a third of its surface, that covered by dry land. But the oceans are becoming of greater interest, especially with a NASA series of satellites called Seasat, which emphasise the potential of satellites for solving problems related to ocean currents, pollution of the seas, fisheries and detection of icebergs.

Seasat A was launched in June 1978 but was not a great success for NASA. By October it had been partly disabled, apparently by a short circuit. The hope of Seasat A was to see what was possible – proof-of-concept in NASA's inelegant jargon – and the 99 days of life which was obtained from Seasat A seemed to show that it was. *Aviation Week and Space Technology* quoted Walker A. Giberson, the Seasat A project manager at the NASA Jet Propulsion Laboratory at Pasadena, California, as saying that 'We have seen some magnificent data during the time we have had the sensors operating, and these will fulfil a major part of the proof-of-concept mission.' The concept to be proved could eventually give rise to a global network of ocean observation satellites like the existing network for satellite communications.

Seasat A was armed with an array of sensors including radar, for examining wave heights, ice fields and icebergs, a radiometer for obtaining data on wind speed, temperature and atmospheric water vapour, and a microwave system for examining the surface roughness of the sea caused by winds. Seasat A was to be used as part of the GARP experiment (see above) especially in the Atlantic, west of Scotland. During its short lifetime, Seasat A observed ice cover in Canadian water (proving an ability to tell smooth from rough ice by the stronger radar echo from smoother

surfaces) and also proved itself able to distinguish wind disturbances on the ocean surface of the Pacific. The Gulf Stream was also mapped – it has a complex structure of currents adding up to form the overall Stream – in radar frequencies.

The failure of Seasat A will not mean the end of NASA's attempts to find out the possibilities for ocean surveillance. And in addition, other countries are active in the field including the USSR, which is thought to use some sea data derived from meteorological satellites. The chapter on military uses of space goes into American attempts to obtain oceanic information to help detect Soviet submarines, there are no signs that the USSR is trying to do the same thing, but the temptation to try must be there. Much of the data derived from Seasat A was potentially useful in submarine hunting, especially material on ice cover and wave height.

Although there appears to be no European answer to Seasat, the Japanese are working on a project called MOS-1, a marine observation satellite intended, according to Japan's Space Activities Commission, '. . . for observation of ocean colour, ocean temperatures, and for the establishment of techniques common to Earth observation satellites.' Japan's high dependency on fishing – and the safe arrival of oil tankers from the Middle East – makes ocean surveillance an obvious task for its limited space programme.

The sort of economic advantage the Japanese are looking for was made clear at a Committee on Space Research (COSPAR) symposium on the use of space observations for food information, held in Tel Aviv in 1977. The symposium heard reports on a comparatively successful attempt to predict the distribution of a fish – the menhaden – in the Gulf of Mexico in 1972, using Landsat data. A later experiment was also a partial success, in both menhaden and herring. There are also apparently possibilities for sensing krill, kelp (a seaweed), and ocean concentrations of chlorophyll. This would provide information on plankton in the sea. Plankton is almost at the bottom of the marine food chain, and high fish concen-

trations are found feeding off it. The plankton are brought to the surface by upswellings of cold water, and surface temperature is one of the easiest things about the ocean to measure from space. This is because the temperature of a body influences the amount of infrared radiation it gives out – devices to measure heat output from different parts of the Earth's surface do so by measuring the amount of different wavelengths of infrared light they pull out. The Earth's atmosphere does not impede infrared radiation. Upswellings of hot or cold water therefore stand out dramatically in any infrared view of the oceans. In a world where fast-growing fish catches and possible limits on what can be caught – are making fish and the oceans highly political; countries increasingly want the information advantage offered by remote sensing of the oceans, not least because one of the things it can do is to spot fishing boats in the act.

Apart from communications – dealt with in another chapter – the other main benefit from satellites and the ocean relates to navigation. Satellite navigation was hit upon by navies many years ago as a probable way of providing the highly accurate navigation needed, particularly by nuclear missile submarines. These often have as targets missile silos just a few metres in diameter, which must be hit accurately if they are to be destroyed. The US Airforce's Navstar system is the culmination of the Department of Defense's work on Satnav, as it is known. Now under development the Navstar system will provide global coverage and give positions to within a few metres on the Earth's surface for ships, aircraft and land vehicles. Existing Satnav systems already give different answers at the stern or bow of the ship, which presumably means that no improvement in accuracy would be sensible. The satellite industry expects even small ships to have Satnav before too long, making many complex navigation techniques redundant. What they expect is that the Navstar system, or something like it, will eventually be made available for civilian use, allowing even the smallest ships to have precise navigation information in any weather, provided their Navstar receivers go on working.

Competition for Landsat

Most of this chapter has been about American efforts on remote sensing. This is inevitable for a number of reasons, mainly because of Landsat. That one modest programme has turned remote sensing from an idea into a reality, an economic fact acknowledged by planners, agricultural ministers, spies, geologists and all manner of other people all over the world. In addition, information about Soviet remote sensing is difficult to come by. On the other hand, remote sensing is, after communications, the most attractive field for new entrants into space, whether their interests are primarily military or civilian.

For this reason one of the European Space Agency's main projects is to develop a European remote sensing

capability independent of American resources, but leaning on knowledge gained primarily from Landsat. Meteosat, ESA's first meteorological satellite was placed in orbit in November 1977 to provide data on the weather over Europe and Africa from a geostationary orbit. 1981 is scheduled as the date for the launch of Meteosat 2 – which is a refurbished Meteosat 1 engineering prototype – and ESA hopes that Meteosat 2 will go into orbit on the third launch of its own Ariane launcher, and thus be the second of a series.

Meteosat 1, which was sited above the Gulf of Guinea, was used to produce images of the Earth's surface and cloud cover at half-hourly intervals, and to receive and re-transmit data from ground stations. The imaging was done in visible and in infrared light. One IR channel was designed to look at temperature and the other at a waveband blocked by water vapour, to show atmospheric humidity. The programme of data collection from remote Data-Collection Platforms (DCPs) involved ships, buoys, balloons and aircraft, including a package fixed to wide-bodied airliners, sending their position as well as information on the weather around them via Meteosat to a ground base at Lannion in France.

A 1971 US-Soviet pact on joint investigations into the environment by means of space technology has produced some information on Russian efforts in the field. For instance, mineral deposits have been investigated with the aim of sorting out the large-scale geological structure of the Caspian area, and an oil- and gas-bearing region; and previously unknown fault patterns were detected according to the USSR's Geology Minister, Alexander Sidorenko, in 1975. The Gulf of Kara Bogaz, a vast mineral trap near the Caspian Sea, was also being investigated. Unusually, the Soviet announcement of these investigations gave no clue of the satellite making them, suggesting that it may well have been a military spy satellite.

It appears that much of the Soviet remote sensing effort has been carried out from manned missions, of which the Soviets have flown more in recent years than the Americans. In 1976, for instance, the two-man crew Salyut 5 orbital station, who had been trained extensively before

the flight in geology, geophysics and materials science, went into orbit. The Salyut 5 cosmonauts carried out tasks like the visual inspection of the Soviet land mass with a view to compiling maps on a large scale, analysing geological structures in order to identify petroleum and minerals, and examining areas near to potential large dam projects. They also looked out for forest fire hazards and examined the area at the little-known eastern end of the proposed Baikal Amur railroad

It is possible that the Russians plan to make their main remote sensing effort from the manned space stations which they seem intent on establishing, although they are known to have a series of weather satellites the Meteor series – and these probably send back information about ground conditions as well. There are also military spy satellites whose output may be available to a civilian agency At the time of the Salyut 5 flight, the Russians announced that space survey materials had already been used to make geological, geomorphological, soil and water maps of parts of the USSR, and to produce ' an environmental protection atlas of the Crimean Peninsula '

The task would have been impossible without satellites The atlas apparently gives details of the erosion, salt damage to the land, ground water and irrigation And the Russians added that in clear weather '. . . the Salyut 5 crew can see oil fields which were started there (the Caspian Sea area) according to geological forecasts made from outer space.' They exaggerate. It requires close ground work to decide where to drill for oil But a look from space can certainly help, as William V. Trollinger of Denver and the Russians would doubtless agree

Politics

Remote sensing has been largely developed by Western governments and corporations for their own use It has therefore aroused intense suspicion among many people – including governments in the Third World – who are alarmed at the growing power of a few hundred major corporations over their countries Their fear is simple: the information advantage which remote sensing offers will

reinforce the inequality between the Third World and the Western World, this would not happen to the same extent if an international agency were in charge of disseminating data from Landsat and similar spacecraft. It is feasible, of course, that the declining cost of ground stations and the increasing number of countries getting them, for Landsat data as for telecommunications, will spread the benefit of remote sensing widely. But so far the politics of remote sensing in the world of 'the food weapon' seem likely to remain complex.

Attempts to get around this apparent monopoly have not been particularly successful so far. Japan and Europe have remote sensing programmes, but they hardly count among the Wretched of the Earth. Otrag, the German firm set up in Zaire to launch cheap satellites for the Third World, has now been expelled from there and seems to be setting up in Latin America, assuming that it is not simply a tax-loss device for the German middle classes (more of that in the chapter on the military uses of space.) But one possibility is that Indonesia, already setting up satellite communications for South East Asia, may go into remote sensing next. This could give the Third World an inside track which it does not have at present.

For instance, a study of multinational corporations' control of food supplies published in 1979 by Susan George of the Institute for Policy Studies in Amsterdam, *Feeding the Few*, described the US Large Areas Crop Inventory Experiment run by NASA, the NOAA, and the US Department of Agriculture as 'a powerful new tool serving American domination of world grain markets.' She points out that LACIE, after a trial run in the US Plains, was being used to assess output from all the USA's main competitors in grain production, and that this was done without the agreement of the other countries except for Canada. According to George only the multi-nationals and the US government have the personnel to interpret the Landsat data. a Canadian MP she contacted says that even the Canadians are unable to analyse the huge amount of data that Landsat produces which is relevant to them. Third World countries would almost certainly be in a far worse position. George quotes the example of Remote

Sensing Engineering Limited, a firm set up to offer the benefits of remote sensing in Latin America. Its clients so far include mainly large corporations, but obviously small farmers and almost landless peasants are unlikely to benefit.

Latin American countries first viewed Landsat with intense suspicion as a way for the USA, and perhaps their own neighbours, to spy on them. The same was true in Africa when Otrag was established in Zaire. Later, many Latin American governments started to use Landsat data, having decided that at worst it was something they would have to live with. In July 1978 *Aviation Week and Space Technology* reported that the Inter-American Development Bank, which had put $5.2 million into remote sensing projects in the previous five years was to double that amount on projects involving Landsat data in Argentina, Peru, Honduras, El Salvador, Nicaragua, Costa Rica, Guatemala and Bolivia. Argentina was planning to get a Landsat ground station. In the case of Peru it was deserts and their spreading that was of interest, while in Central America, forestry, minerals and water were the targets. Bolivia had already used Landsat data extensively, mainly for geological surveys, a population and census survey, and other projects such as deciding the best routes for a railway and a gas pipeline.

The politics of remote sensing in Latin America have been controversial. In 1975 Brazil became the continent's first country to have a Landsat Earth station and an argument blew up with NASA over Brazil's refusal to supply Landsat data to its neighbour. NASA threatened to cut off Brazil's supply of Landsat transmissions unless the data was made available, and at a reasonable price. Brazil was forced to do so.

The politics of remote sensing were summed up by Irma Adelman, Professor of Economics at the University of Maryland, and a member of the US National Academy of Sciences ad hoc committee on remote sensing and development mentioned above. The committee reported favourably about the prospects of remote sensing as a tool for the Third World, but in Adelman's dissenting statement she took the view that any effort '. . . to evaluate the

possible effects of a new technology upon developing countries must take into account the potential impact of that technology on the poor people of those countries', and that historically this has rarely happened. The poor will only be helped, according to Adelman, if '. . . specific, conscious and determined steps' are taken to make sure that they are, and that US programmes involving remote sensing – especially foreign aid programmes should be framed with that in mind.

The Future

It seems likely that the Third World will have to live with remote sensing and that even the achievements of Landsat will eventually be dwarfed by Landsat D, its suped-up successor, and after that some even more exotic remote sensing satellites. Landsat D, which may be launched in 1981, is being developed by the Space Division of General Electric. The development of Landsat D is inseparable from the American politics surrounding the commercial future of remote sensing recounted above, but it will be tied into the Navstar navigation system as well as the TRW/Western Union ground station systems. The American have not yet finalised what Landsat D will do, and there is likely to be political wrangling over the ground resolution it will be allowed to reveal, since the pictures it produces will probably all be available to the public

In the longer term, the sort of remote sensing project being contemplated by the Americans is typified by a study being carried out by NASA's Goddard Space Flight Center and the GE Space Division, entitled 'Post Landsat D Advanced Concept Evaluation, PLACE.' The ideas include Geos, the Geosynchronous Earth Observation System, a large telescope in orbit which could give a 3 m ground resolution Disaster assessment is advertised as the main use, although others appear to spring to mind. PLACE is looking at a dozen ideas, including an advanced Landsat, Landsat H, and devices for looking at soil moisture, vegetation quality, and other ground-level details. One idea studied, the texturometer, is an optical device to identify surface materials with a resolution down

to somewhere in the 1 mm – 1 m range. Another, the Force Wheel radar, would be 30 km across and would use radar waves at very low frequencies, 30 – 300 megahertz. This would allow details of subsurface geology to be examined. If the PLACE ideas come to anything, keeping secrets will be very difficult towards the end of the twentieth century.

5 War in Space

Early in the morning of 24 January 1978, the almost twenty-four hour darkness close to the Arctic Circle in Canada was disturbed by the unplanned arrival from outer space of an object weighing over 250 kg. It was a Soviet satellite, Cosmos 954, and it had been engaged in espionage. Cosmos 954 was powered by a small nuclear reactor and it was a blessing that it plunged to Earth some 350 km from the nearest centre of population, since it was out of control, it could have hit Ottawa. Cosmos 954 was spectacular evidence – rapidly seized by American and Canadian military scientists – of the military uses of space, for over 20 years perhaps the most powerful justification for space exploration.

Most satellites gain enough power for their needs from solar energy, so the fact that Cosmos 954 had been fitted with a nuclear reactor – containing over 50 kg of nuclear fuel – fed American suspicions that it had been engaged in an exotic and very energy-demanding game of laser sharpshooting to destroy American military satellites. Although this was hotly denied by the USSR's Academician Leonid Sedov, he did not claim that Cosmos 954 had not been military in intention. US authorities have concluded that Cosmos 954 had probably been tracking US naval movements before it was pushed out of its orbit. Perhaps Cosmos 954 was fitted with a nuclear reactor for fear of other satellites blinding it with laser beams if it had solar cells – we shall probably never know, as we shall never know whether it was disabled by an attack or by a stray meteorite. As this book was being written, the Cosmos 954 saga was continuing with a $12 million Canadian lawsuit against the USSR.

There are many other examples of how seriously the military takes space, associated for example with recon-

naissance satellites. During and just before the Middle East War of October 1973, the Soviet Union launched no fewer than six spy satellites, all of them placed in orbits designed to allow them to pass low over the Middle East battlefields and observe fighting on the Egyptian and Syrian fronts, and in the air above them, as well as to observe the movements of the US Sixth Fleet in the Mediterranean.

The satellites involved – Cosmos 596, 597, 598, 599, 600 and 602 – were designed to spend two weeks in orbit photographing Middle Eastern targets and then eject a capsule containing the film taken. The capsules made parachute descents over Soviet territory. Satellites like these, which can manoeuvre in orbit to get a close look at small areas of the Earth's surface, are regarded by American observers as a prime indicator of Soviet interest in particular parts of the world, especially when launched in large numbers. Presumably the Russians carry out the same calculus about American launches.

The figures show that war and space have so far been closely linked. About 60 per cent of satellite launches – some 1500 spacecraft since the start of the 'space age' – are thought to have been military in intention, and it is military satellites which have persistently been the leaders in space technology, with advanced steering equipment, cameras and communications which only later work their way through to civilian uses. Military satellites are primarily engaged in espionage – spying on the military and industrial activities of actual or potential enemies. They are widely used for electronic intelligence, listening to wireless, telephone, telex and other communications traffic. (Electronic intelligence in space and on land now greatly exceeds in volume all manner of traditional cloak and dagger spying.) Other military uses of space include navigation and geodetics, the science of measuring the Earth's size and shape very precisely. This allows missiles to be aimed accurately at small targets across thousands of kilometres. We are also now beginning to see the superpowers limbering up for actual conflict in space, in which satellites and space stations themselves fight extraordinary space battles.

From the beginning of the era of manned spaceflight, the

military interest in space has been apparent from the dominance of air force personnel among both Soviet and US astronauts. From Yuri Gagarin onwards, most astronauts have been military fliers, even after it became apparent that the stresses of launch and re-entry could be withstood by people without years of experience in fighter flying. Now astronomers, metallurgists, biologists and other scientists are going into space in increasing numbers, but it is unlikely that they are going there for wholly peaceful reasons.

Organisations which try to monitor the warlike uses of space have to cope with the problem that there are usually few distinctive features to tell observers which space missions are doing specifically military work. Sometimes there are, such as a satellite which manoeuvres low over Middle Eastern battlefields or which steers itself close to another satellite which mysteriously ceases transmission. But most of the things which military satellites do, like watching the weather or carrying telecommunications, are very similar to civilian tasks. The similarity extends back to the technology for getting them into orbit, which is generally done with the same rockets. Thus US military satellites have been launched by Atlas and Titan rockets, both originally inter-continental ballistic missiles now widely used for launching satellites. Other rockets used for launching US, British and French satellites include Thor, Atlas-Agena and Scout. And the same split-second techniques of timing are used to get both military and civilian satellites into the right orbits. The Soviet Union also uses a converted ICBM, the Sapwood, for many of its military and civilian launches.

One way in which military satellites differ from their civilian kin is control. Military satellites have pioneered the art of manoeuvrability in space, which so far seems to have had little civilian use. The first Soviet satellite to manoeuvre in orbit and eject packages for retrieval in the USSR are now common. These are almost certainly reconnaissance satellites used to get a close look at areas of particular interest to the USSR, and they usually have lifetimes in orbit of about a fortnight. The steering is done by small rockets in response to telemetred commands from the

ground. In the same way, the US Big Bird satellites obtain their long lives in space by manoeuvring to compensate for the natural decay of their orbits. Reconnaissance satellites have relatively low orbits, where they are slowed down by drag from the uppermost layers of the Earth's atmosphere, so that they cannot last indefinitely in orbit without the ability to steer.

Recent advances in microelectronics mean that more and more control functions will be carried out on board military satellites rather than by instructions from the ground, in much the same way as some authorities expect communications satellites to take over some of the functions of the telephone exchange. Some military tasks, like attacking ballistic missiles or other satellites with lasers or beam weapons, require incredibly fast and well co-ordinated action which can perhaps best be carried out automatically in space. The sort of satellite which the superpowers will be using for space warfare will be so complex, with radar sensors, computers and the like on board, that they will not operate simply by exploding near their quarry – laser weapons and beam weapons will be preferred.

Progress in telecommunications means that increasing numbers of military satellites are sending information back to Earth as coded radio signals. High quality pictures can be transmitted in much the same way as TV programmes. Despite the cheapness and speed of transmitting intelligence data by radio links, the time honoured method of dropping packages from satellites will also continue to be used. This is mainly because it offers absolute security, whereas radio traffic can always be intercepted. The packages are recovered either from the ground or from mid-air, usually by helicopters a few thousand feet above ground level.

The military uses of space are in principle circumscribed by a number of international treaties. The main one is the 1967 treaty on the exploration and use of outer space, including the Moon and other planets. The original signatories to this treaty were the USA, the USSR and the UK, and 74 other countries (including France but not China) have now joined these three in agreeing to carry on

their space activities 'in the interest of maintaining international peace and security', although most of the signatory nations do not have the ability to enter space for peaceful or warlike purposes. In addition, there are two earlier treaties forbidding placing or exploding nuclear weapons in space.

This is undoubtedly a benefit to international security, since nuclear weapons launched at the Earth from space would be virtually unstoppable and there might be no way of telling which country had launched them. Other aspects of the military uses of space are also clearly beneficial to world peace, in particular surveillance of countries which might be developing their own nuclear weapons. South Africa, of which more later, is a case in point. But in general, the consequences of the development of the space battlefield could be enormously dangerous for those left below. The space programmes of the USA and the USSR grew directly out of World War 2 rocket experiments in Germany, so it may be that the most terrible consequences of that war are only just becoming apparent.

For the superpowers, space is primarily a place to carry on espionage. The vast flow of information about military, industrial and scientific developments which can be obtained from space gives powers with the ability to gather and process it a vast lead on their rivals, especially because powers which have the ability to use space can usually back it up with military muscle on the ground. Intelligence gained from orbiting platforms like the US Big Bird satellite, and spy satellites in the Soviet Cosmos series, is essentially a more sophisticated version of the intelligence gathered by high-flying aircraft like the American U2 and SR-71, with the important difference that it can be gathered with far less risk of political embarrassment.

Like reconnaissance aircraft, spy satellites look at the Earth's surface in both normal light wavelengths and infrared light. Each waveband has its own uses, particularly because pictures can be taken in colour using different parts of the light or infrared spectrum. Infrared radiation – heat – is useful for detecting military or industrial sites, from rocket launching sites to steelworks, where heat is released into the atmosphere in large

quantities. (Infrared frequencies are also used to examine crops, a non-military use of space with vast peaceful applications.) Infrared detectors in Big Bird satellites gave the US authorities their first suspicions about a Soviet plant at which nuclear reactors for use in space seem to be under development.

The intelligence-gathering potential of even one spy satellite is vast. At the usual altitude of 150 km, it can view more than four million square kilometres of the Earth's surface. And cameras and films now in use allow that area to be viewed closely, especially the part of it directly beneath the satellite.

In the last few years, Soviet and American satellites have been used to observe most of the world's political trouble spots in the same way as the October 1973 war in the Middle East was observed by Soviet Cosmos satellites. The exact missions which spy satellites carry out are rarely publicised, but observations of their orbits and the data they return to Earth allow many deductions to be made about their use, especially in the context of political developments occurring at the same time.

An example of this is the US Big Bird satellite 1974-20A, and the USSR's Cosmos 653. 1974-20A was launched on 10 April 1974 and Cosmos 653 on 15 May 1974. The pair had similar orbits which carried them over India at the time of India's first, and so far only, nuclear weapon test. The Soviet satellite was launched only three days before the explosion on 18 May, suggesting that the Americans had better intelligence about the Indians' plans. Although the Big Bird satellite passed to the East of the Pokharan test site on the 18th, it was close enough to observe the 150 m crater made by the underground explosion. Cosmos 653 came even closer to being over the site on the day of the test. Despite the argument that such surveillance makes it harder for nations to make warlike plans in private, and thus helps the prospects for peace, the prime purpose of spying from space is to give a military advantage to the watcher, in this case both the USA and the USSR.

This was the function of two satellites launched just a few weeks later, 1974-65A from the USA and Cosmos 666 from the USSR. These were both used to overfly an area that

included Greece, Turkey and Cyprus at the time of the Turkish invasion of Cyprus and the army coup which preceded it. American and British interests were vitally involved. For instance, Cyprus houses a British listening post which intercepts radio traffic in the Middle Eastern area as well as a Royal Air Force base, RAF Akrotiri, from which the US Air Force makes flights in U2 spy planes over Israel and its neighbours. Cosmos 666 was launched on 12 July, just before the coup and a week before the invasion, and was on hand to observe both. 1974 65A was not launched until August, missing both events, but was available to observe the progress of the invasion. By a skilful piece of positioning, 1974-65A was able to make southbound passes over the area in the mornings and northbound ones in the afternoons, although it made only two passes over Cyprus to Cosmos 666's four. In addition, Cosmos 667 was manoeuvred in its orbit to give some coverage of Cyprus and 1974-20A, the same Big Bird used to monitor India's nuclear test, made three passes over the island. These were particularly propitious – one was on 15 July at 10.25, a cloudfree morning chosen for the army coup. The next pass was on 20 July, the day the invasion began, and the last was a few days later, on the 25th. Big Bird's orbital manoeuvrability offers the USA a particularly large information advantage in fast-moving situations like Cyprus in mid-1974.

In addition to these impressive and militarily useful feats, the superpowers observed the 1971 Bangladesh war from space, and have devoted considerable investment to watching countries which seem to be trying to acquire their own space rocketry or nuclear weapons. These have included South Africa and its northerly neighbour Zaire, both of which were closely observed in July 1977 by Soviet and American satellites, including 1977-56A, another Big Bird satellite, and Cosmos 922 and 932. All these passed over the OTRAG rocket range in Zaire and a possible South African nuclear test site near the Botswana border, deep in the Kalahari desert. It seems that the Soviet announcement that the South Africans seemed to be on the point of exploding a nuclear weapon may have prevented the test from being carried out. But the fact that the

American Big Bird satellite was already in orbit indicates that the Americans, too, had an idea of the goings-on in the Kalahari. This could have been obtained from West Germany, the source of most of South Africa's nuclear know-how.

These spectacular space interventions in world crisis points are the tip of a huge surveillance iceberg, the majority of which consists of day to day surveillance of military and industrial sites, like the Soviet reactor centre mentioned above.

There is little doubt that manned space missions, which are becoming easier and cheaper to carry out with Soviet and American projects to establish permanent manned space stations and cheap ways of getting material into orbit, will facilitate espionage from space. Money is already being spent on adaptations to allow the space shuttle orbiter to capture passing satellites. Although one of the earliest U'S Gemini astronauts commented how easily he could observe boats moving on the Nile, he was no doubt also asked to look for less traditional military technology in the same area. Although there may at some stage be genuine spies in orbit, most of the future developments in space surveillance, and other military uses of space, will involve unmanned spacecraft.

A key question is the quality of the data which can be obtained from spy satellites. In general, the quality is surprisingly high, and provided there is no cloud cover atmospheric disturbances seem not to affect image quality. (In contrast, the performance of telescopes looking into space from the Earth is usually limited by atmospheric turbulence.) The limitation on satellite photography is mainly to do with the size of camera which can be placed in orbit. 460 mm focal length lenses – like one which a very well equipped terrestrial photographer might have but with a wider diameter – have been used in Skylab cameras and there seems little reason why 600 mm lenses should not be used – perhaps they have been already. Given modern computer techniques to correct for lenses' optical imperfections, it ought to be possible to get photographs of the Earth's surface with detail visible to about 15 cm in size. It is already possible to distinguish between different types of

aircraft on military runways.

In addition, new technologies are starting to come into use which allow the image contrast in photographs to be enhanced, so that comparatively detailed photographs can be taken at night, especially if there is some moonlight available. Laser 'torches' can also be used at night, although these would mean that whoever was being watched could become aware of the surveillance, which is not normally possible if the watcher is in orbit. In addition, existing radar technology can be used from space. Its resolution is very low – less than a kilometre – but it is unaffected by dark or clouds.

Up to the end of 1976, according to one set of experts, the USA had launched 224 photographic reconnaissance satellites, while the USSR had managed 363 and China two. There is room for argument about the totals, but there is no doubt that military snooping from space is a major priority for both superpowers. The ability to take a close look at almost any part of the Earth's surface is a huge military advantage to each.

In the course of just a few weeks, photographic and electronic intelligence satellites pass over virtually the whole of the Earth's surface. A major industry has grown up analysing the data they collect. There are relatively few targets in the Third World of enough interest to warrant satellite surveillance – only something as special as a war or a potential nuclear weapons test, to choose two recent cases, is likely to be judged worth a look. Instead, the USA and the USSR concentrate mainly on looking at each other's army bases, naval dockyards, space centres, research establishments, and so on. In addition, some industrial locations like nuclear power stations, shipyards, airports and the like are thought to be under regular surveillance. In one US disclosure about an accident at a Soviet nuclear power plant on the Black Sea, satellite observation was specifically mentioned as the source of the American knowledge. The extent to which nominally allied nations are kept under surveillance is less clear.

This surveillance is carried out because, although most intelligence is obtained from open sources, the small percentage which can only be got clandestinely is the most

important. For instance, the effectiveness of the treaty banning atmospheric nuclear weapons tests is policed by monitoring stations in Norway, the UK, the USA and elsewhere, and by sensors in space. Secret military developments can only be observed by espionage, either from the ground or from satellites or high-flying aircraft.

Spacecraft have allowed a vast increase in the quantity of intelligence available to the superpowers, and made it much more difficult for anything to be kept secret from them. It would probably be an exaggeration to call this a fundamental shift in the world balance of power, which has always tilted in the superpowers' favour, but the importance of satellite intelligence is growing fast as it becomes cheaper and more comprehensive.

As well as looking directly at the Earth's surface, satellites can listen to other countries' telecommunications – radio, telephone, telex and the like – both military and civilian. Most land-based espionage is carried out by listening to communications rather than by snooping about in foreign countries and there is a large amount of equipment at the Earth's surface for such listening. It is gradually being replaced and supplemented by satellite systems.

There are a number of advantages to having listening equipment in space, one major one being that the risk of political embarrassment is much reduced. In 1976 the Americans were forced to make a rapid exit from one listening post in Thailand, and the same thing happened in Iran in 1979. This danger also exists in Saudi Arabia, and US listening posts have recently been closed down and then re-opened in Turkey – a fellow NATO country – as a result of the country's disagreement with the USA over Cyprus.

Nearly 100 electronic reconnaissance satellites have been launched by the USA and the USSR, and their main purpose is to get the measure of enemy radar installations meant to provide early warning of missile or aircraft attack. It is comparatively easy to pick up the radar signals as they pass into space. The same techniques are probably also in use more and more to listen to the whole range of telecommunications, not necessarily military.

There are other far-reaching uses to which military

surveillance satellites could be put, including keeping a precise eye on developments in the oceans. This is now done with much the same cameras as are used for land surveillance. Radar is also widely used for examining the ocean surface and Cosmos 954, whose untimely and suspicious end began this chapter, seems to have been observing US naval movements by radar before it interrupted the Canadian winter so abruptly.

The use of infrared heat detecting devices in satellites, mentioned above, offers one important additional benefit. As well as detecting newly launched missiles, it makes it possible to detect nuclear submarines, both missile carriers and the hunter-killers which stalk them. The idea of nuclear missile submarines is that they should be undetectable and so indestructible, so that their missiles remain as a deterrent even if land-based missiles were destroyed in an enemy 'first strike'. It seems that this strategic advantage could be wiped out during the 1980s. And the use of high-resolution radar and cameras will mean that small surface ships will be less able to hide than before, giving the superpowers and their clients an advantage in even minor conflicts.

After spying, the most important military activity in space is communications. Civilian satellites are used mainly for communications and communication satellites have replaced cables as the main carriers of telecommunications traffic on major routes like North America to Europe and Europe to the Middle East. Even in the early days of Echo and Telstar, it was widely thought that communications would be a major use for space; the fact that armed forces would do most of the talking was less widely appreciated.

There are a number of reasons for the rapid adoption of satellite communications by the military, but the most important is that war itself has become vastly more dangerous and fast-moving in recent years. For instance, states which plan to use nuclear weapons must have a virtually instantaneous method of co-ordinating aircraft, ships, missile sites and command centres if they are to use them in time of war. And these communications links must be secure against disruption or decipherment. Satellite communications offer the potential for all this, and the offer has been taken up with enthusiasm. Satellites also

offer the ability to communicate without complex cable links and, usually, without the need to worry about atmospheric interference. And with computer technology, satellites offer unrivalled opportunities to couple the grand strategic picture with battlefield radio links, allowing unprecedented control of fighting forces.

The US satellite programme for military communications is thought by experts to be more comprehensive, at the moment, than anything being attempted by the Soviet Union. The mainstay of the US system is DSCS, the Defence Satellite Communications System, which will ultimately consist of no fewer than 15 satellites providing almost instantaneous communications between US forces anywhere on the globe. The system is the successor to the 26-satellite Initial Defence Communications Satellite System, in which global coverage was provided by a mixture of polar orbiting and geosynchronous (stationary above the Earth's equator) satellites. DSCS will eventually carry American diplomatic telecommunications, intelligence reports, early warning data, and a whole gamut of other information, but primarily the World-Wide Military Command and Control System, WWMCCS, a complete data system for all kinds of military command.

WWMCCS consists of two parts. The first and more spectacular is the high-capacity SHF (super high frequency) system to provide international co-ordination between US commanders. The second is a low-speed teletype system for battlefield communications. It amounts to a new dimension in military communications, especially in tandem with other US systems under development. These include 3000 m diameter antennae to allow communications with 1000 wrist radios over a large land area, which could be used equally for battlefield control or espionage.

The two main systems now being put into use by the US military are AFSATCOM, for the US Air Force, and FLTSATCOM, for the US Navy. The former, which means Air Force Satellite Communication Network, is designed as a low-speed teletype system to allow almost unjammable messages to be carried between USAF units, on the ground as well as in the air. The system would link

into DSCS and has been designed so that satellites and ground stations can be destroyed without data being lost, in other words with a high degree of redundancy, showing that its planners take the threat of satellite warfare seriously.

The US Navy system, Fleet Satellite Communications, involves four main satellites plus a spare and transmits intelligence, weather reports and other data to Navy vessels and shore stations. This system is one of the first to provide for computer to computer data movements, a type of communication of growing importance for both military and civilian users.

While the USA had launched 100 military communications satellites by late 1976, the USSR had orbited no fewer than 206, but little is known about most of them The USSR lacks the worldwide spread of military bases which US commanders take for granted, so that the USSR has instead built several surface vessels for satellite communications. The best known is the *Kosmonaut Yuri Gagarin.* So far a number of Soviet military communications systems dependent on satellites have been identified by Western observers, and most seem to involve members of the Molinya series of satellites, of which 51 were launched between 1965 and 1976 In 1977, Cosmos 923 and 968 are thought to have been launched for military communications.

The Molinya satellites have a large capacity for voice and TV traffic. They have so far been placed in highly inclined orbits 90 apart so that there is always one over the USSR, allowing continuous coverage. But in late 1975 the launch of Statsionar 1 marked the USSR's first military use of synchronous satellites. These are of restricted use within the USSR because they have to be in a position directly above the equator, far to the south of the bulk of Russia. There will eventually be 10 Statsionar satellites, some at least partly for civilian use but primarily, it seems, with the intention of communicating with Soviet forces away from home.

Although little is known about Soviet military satellites, it is probable that schemes like the 3000m aerial for fabrication in space under study in the USA are also

receiving attention in the USSR. That sort of system, which offers the potential for simplifying and improving battlefield communication and replacing large ground radios with miniature, even wrist-watch sized, ones, is obviously irresistible to the military.

Military communications in space will presumably continue to become more elaborate and more indispensable for modern warfare. In the same way, efforts to interfere with communications satellites and their transmisions will doubtless intensify. So far the military use of space has mainly strengthened the hand of the superpowers, which have a virtual monopoly of the operational advantages of instantaneous communications worldwide. The USA has been able to oblige its NATO partners by launching two satellites for them, but it would be unlikely to do the same for less firm allies. In the future, more general access to satellite launching facilities may change all that, with France, China and other countries already carrying out their own launches.

The superpowers are carrying on what amounts to an arms race in space, building up vast espionage and communications networks. Like any arms race, this one carries with it the danger of war – space is new potential battleground where neither side wants to be number two. There are already signs that the USA and the USSR are preparing for the first war in space, by testing in space and on the ground a new generation of weapons which could be used to destroy enemy satellites at will. The sort of war they might wage is hard to imagine, but space war would be part of any future world war because of the vital role of satellite intelligence and communications links. The destruction of such links would be a first priority in a future world war.

For over a decade, the USSR has been gaining experience of space war with mock battles in orbit between target and hunter satellites. Enough of these exercises have ended in the destruction of the target for the USSR's ability to wage space war to be unquestioned. Unfortunately, far less is known about American potential, since all the facts about the Soviet programme have come from the US intelligence sources in the hope of improving the climate in the USA for expensive space weapons research. According

to US sources, at least 19 Cosmos satellites were launched for space war trials between 1968 and 1976, and at that stage the foundations were just being laid. These satellites were launched from the main Soviet launching sites at Tyuratam and Plesetsk, and were all put into orbits inclined at 61-66° to the equator. The target satellites' orbits tended to take below 100 minutes, with the hunters' taking a little longer.

Neither the Russians nor the Americans are saying just what the hunter satellites did when they got close to their prey, but these tests took place before lasers and other space weaponry had been properly developed. It seems that the hunters 'killed' by simply manoeuvring close to the target satellites and exploding there – even the manoeuvring, remember, is a formidable achievement. A close explosion can disable a satellite by shattering it with debris, smashing its solar cells, or pushing it out of orbit. Satellites which might be subject to this sort of attack are now built more heftily than non-military ones and, like Cosmos 954, have nuclear power plant instead of solar cells. But it is still hard to see how spacecraft can be protected from damage or destruction by explosions nearby. And more sophisticated forms of attack are on the way, as we shall see.

Experiments now going on in the USA, the USSR and France allow us to say quite a lot about what space weaponry might be like when it goes into space. For instance, US Army experiments on the space beam weapon Sipapu indicate that it would use mainly existing technology to find targets, point the gun at them, and keep it firing at them until the damage is done – acquisition, pointing and tracking, to use the jargon. Only the gun itself would be truly novel.

The gun would resemble the sort of particle accelerator used to produce streams of sub-atomic particles for physics research or medicine. Designs are tentative, but the Sipapu experiments so far indicate that it may be possible to get around the problem of accelerating the positively-charged protons which the gun would shoot by first accelerating electrons (a process carried on in every TV tube) and then adding protons to the electron stream. The protons could be produced by electrons from atoms of hydrogen. The

spacecraft would have to carry its own hydrogen, which would eventually run out. The electron beam would have a current of 30,000 amps and 30 million electron volts of energy would be put behind each electron. The problem which remains is to transfer the energy from the electrons to the protons – that remains for further experiments.

Experiments like Sipapu give us at least an idea of what a war in space might be like. Although it would depend largely upon orbiting equipment hundreds of kilometres above our heads, ground-based weaponry including rockets, lasers and possibly particle beam weapons would also be important, increasing the number of targets on the Earth which would be likely to receive a nuclear weapon strike in wartime.

At least $15 million of the Pentagon's money has already been spent on Sipapu, which is being developed at the Los Alamos Scientific Laboratory, where the first atomic bomb was developed. It is no secret that Sipapu, which may be tested around 1983, leans heavily on work carried out in the USSR by V. G. Dudnikov of the Novosibirsk Institute of Nuclear Physics. The Russians are involved in a series of beam weapons experiments including one on electron beams being carried out jointly with France. This may be the first East-West collaboration on what may turn out to be a major weapons system.

According to U.S. intelligence sources quoted in American magazines (such sources are in the business of exaggerating Soviet military abilities) the USSR has already tested electron beams in space from manned and unmanned spacecraft. Electron beams have also been used experimentally in steering spacecraft. This application has massive peaceful potential, but the main beneficiary would be the military, because it wants to be able to manoeuvre spacecraft close together to allow them to be destroyed more easily. Ground based experiments have also been carried out at a laboratory near Gorki, which has a large purpose-built accelerator. Other Soviet experiments involve a powerful laser weapon being developed in a subterranean laboratory near Moscow and a nuclear laboratory near Semipalatinsk where a nuclear reactor for space weapons may be under development. The Americans

are also developing such a reactor, to which we shall come soon.

Soviet research on space weapons seems to be very active For instance, seven Soviet satellites launched in 1977 and 1978 seem to have been involved in space weapons research. Although it is unclear how much success the tests had, US Department of Defense officials do not dispute that late in 1977 Cosmos 970 succeeded in destroying Cosmos 967 at a distance, indicating that the Russians already have considerable destructive capability in space.

Although little is known about the Soviet space weapon experiments except via US sources, it is possible to be fairly definite about the joint French Soviet tests They have been going on since January 1975 and have involved measuring what happens to electron beams in the magnetic and electric fields near the Earth. These tests have peaceful applications, for instance in measuring winds in the Earth's upper atmosphere, but are also essential to firing beams of charged particles, like the electrons used in the tests The tests have been carried out so far from rockets launched at the French test site on Kerguelen in the Indian Ocean

Most of the accounts of space weapons research centre upon laser weapons, with good reason – lasers, light sources which collect radiation from a lamp and emit it in short, very intense bursts, are proven technologically and are in everyday use in terrestrial factories as well as for scientific research. There is a US Air Force programme which aims to produce a usable space laser weapon within a few years, involving equipment now being set up in the cloud-free southern deserts of the USA to test the potential for laser weapons. The USAF plans to place two high-powered laser weapons, one on a mountaintop in New Mexico and one in California, in positions on either side of the USA, to catch satellites overflying US territory in the crossfire. The weapons would be built at a plant at the USAF's weapons laboratory at Kirtland Air Force Base in New Mexico. The same technology may also be used against cruise missiles and small ships - a laser gun has already shot down an anti-tank missile which accounts for the interest in laser weapons from other US armed forces.

Laser weapons would work by heating up enemy spacecraft and destroying their metal skin, their electronics, or their solar collectors This needs a lot of energy, and one reason for the USAF's confidence that its laser weapon will work is that a nuclear reactor to supply the necessary power is already under development at Los Alamos. This reactor, which might also be used to power particle beam weapons, already exists on the ground. A reactor for use in space would not need the protective shielding which is needed on Earth to protect the operators and the environment and can, according to Los Alamos, be built with little new technology

Despite their exotic reputation, lasers are technologically familiar. The same cannot be said of particle beam devices, which would involve shooting large numbers of particles familiar mainly from the laboratory Experimenters are now trying to generate these particles in the huge volumes and energies which would be needed to destroy satellites and missiles in space

At the moment the US Army, which is leading American beam weapon research at the specially-formed Accelerator Technology Division again at Los Alamos – is concentrating simply on finding out whether the idea is workable. There are all sorts of problems associated with firing beams of charged particles in space the beams tend to spread out because all the particles carry the same charge and tend to repel each other, and the beam is affected by magnetic and electric fields, which can change rapidly In addition, it may well be literally impossible to fire a beam of charged particles in space because as the beam left the weapon it would build up an opposite charge on the gun firing it, and the particles would be attracted back again. Such weapons may be confined to uses like attacking satellites and ballistic missiles from the ground, where the Earth would carry away any charge left behind on the gun. It seems to be possible for a beam of particles to clear a long narrow passageway through the Earth's atmosphere through which it could travel into space. Such a charged beam would probably consist of electrons, very minute subatomic particles carrying a negative charge.

It is not possible to be so definite about other

experiments related to war in space. For instance, US officials believe that a hydrogen fluoride weapon for use in space is under development at Krasnaya Pakha, some 50 km south of Moscow. Electron beam experiments, in addition to the joint French Soviet ones, have been carried out in orbit by Cosmos 728 and 780 in 1975 and by cosmonauts in manned Soyuz spacecraft. In general, there have been indications that recent advance in manned spaceflight like the Shuttle are oriented towards military use. Although the US Department of Defense in 1976 cut back from 224 to 106 the number of Shuttle missions it plans to fly in 1980-91, that total is still 9 per year And the Shuttle will make spaceflight cheaper, with effects on both military and civilian spaceflight, and it can be adapted to manoeuvre towards and capture satellites.

In 1977, alarm about space weaponry became so general that talks on banning killer satellites were begun between the USA and the USSR. The talks, carried on in Helsinki, Geneva and Vienna, seemed to make little progress although the fact that the USSR had refrained from testing any space weapons for a year by early 1979 was regarded as encouraging by the Soviets. One problem is that it is hard to verify whether promises are kept when they concern hardware in orbit. Land based missiles are, at least in principle, a lot easier to keep an eye on. A more comprehensive version of the treaty banning nuclear weapons from space may eventually result.

In addition to all these exotic space weapons, conventional rocketry has also been used to destroy objects in orbit. As long ago as 1963, a Thor booster launched from Johnston Island in the Pacific came close enough to an orbiting booster to destroy it, although it carried only a dummy warhead. A US Navy project at the same time, Program Skipper, achieved the same effect with rocket-launched space mines. The USSR's experiments with satellites which can match orbits with their quarry and explode there are also a reminder that well-understood weapons technology can be very effective in space.

Many of the military uses of space are connected with the game of nuclear deterrence. For instance, surveillance satellites watch the heartlands of the USA and the USSR

for new developments such as the deployment of new missiles. And infrared heat detectors in orbit, assuming that they can tell missiles from natural gas glares and blast furnaces, should provide the first news that intercontinental ballistic missiles have been fired if ever they are.

In the long term, the prospect is of satellites which will do much more than warn about the danger from nuclear-tipped missiles. A range of weaponry under development by scientists in various countries may provide the means to destroy missiles just after they have taken off, as they rise above the atmosphere. Mostly these weapons are the same as are being developed for satellite killing – lasers and particle beams. The difference is that speed of action is even more essential, because in wartime a weapon would have to strike many missiles in just a few minutes – and the missiles are a meter across at most. Ideally the missiles should be hit immediately they rise above the atmosphere, not least because they are then still above the enemy's territory. And the tendency to put more and more warheads, real and dummy, on each missile means that the best time to strike is before defences are baffled by a huge number of real and false targets.

In the USA, Hughes Aircraft, McDonnell Douglas and General Electric are all busy on laser systems for use against ICBMs. The US Air Force Weapons Laboratory is involved in particle beam research with the same end in view, although at the moment that project has less priority than the laser beam developments. The laser weapons which might be developed could in principle be mounted in space or at the Earth's surface, but there are many advantages to locating them in orbit. Cloud could not get in the way, of course, and mounting the weapons in orbit would allow them to be linked directly to radar and infrared sensors, producing a powerful, integrated and effective space weapon.

These types of weaponry could be ready for use by the mid 1980s according to US Air Force officials quoted in *Aviation Week and Space Technology*. The same weapons might also be used against aircraft or important ground targets. For instance, the President of the USA would in time of nuclear war be on board a converted Boeing 747

aircraft equipped as a command post and proof against any possible attack. It would be interesting to know how the aircraft would keep out a laser attack from space. Space weapons also offer a possible protection against fractional orbital bombardment systems – FOBS which have already been tested by the USSR. These are nuclear weapons which can be launched from Russia and instead of going over the North Pole to the USA, where they can be seen by the BMEWS and DEW early warning systems, would approach from the south. Very little warning of such an attack would be possible but because the warhead would spend long enough in space to do almost a complete orbit of the Earth it could be attacked by space weapons. The DEW line – across Canada and Alaska – and the BMEWS line, which has bases at Clear in Alaska, Thule in Greenland and Fylingdales in Yorkshire, would be quite unable to detect a FOBS attack, which would only be spotted at the last minute by short range radar in the USA.

Apart from satellites equipped with weapons, most military space missions have direct civilian equivalents. Surveillance from space can detect illegal opium crops or the spreading of deserts as well as it can help count enemy tanks, and communications satellites are as happy with birthday greetings as they are with orders to fire.

The same goes for less numerous but equally important military satellites designed to yield military intelligence about the Earth and its atmosphere. The most numerous category of these are meteorological satellites, of which the USA, the USSR, France and the UK had launched about 120 up to the end of 1976, mostly for military purposes These satellites can determine temperature with infrared sensors as well as producing data on wind speed and direction and taking photographs of cloud cover. The type of cloud photograph taken is familiar from TV weather forecasts. The US Air Force has used satellite weather data since the early days of the Tiros weather satellites from 1960 onwards. It now has two large ground stations receiving weather data, one each on the US East and West coasts. These receive data from relay satellites which in turn collect it from ground stations around the world which are in touch with the meteorological satellites. The data is

processed centrally by the USAF Global Weather Center in Offutt Air Force Base, Nebraska. The USAF can also receive weather data at terminals carried in larger aircraft. The US Navy also uses USAF weather data from around the world, and it is likely that both services use weather data from civilian satellites. The Soviet system is thought to be less comprehensive, although the Meteor 2 series, which was started in 1975, may be catching up with American technology.

Satellites are also used by the military for finding exact locations on the Earth's surface. This falls under the twin headings of navigation and geodetics. Navigation by satellite is likely to reach its highest point of perfection for some years in the US Navstar system, consisting of 24 satellites each in a 24 hour orbit, some synchronous about the equator and some in polar orbits. The system will be used by all US forces and will allow positions to be fixed to within about 10 metres and velocity to within some 6 metres per second. Although there are various military applications for this accuracy, the main one is in guiding ICBMs to targets like enemy ICBM silos, which are reinforced and must be hit very accurately if the missile within is to be destroyed. The Navstar system is prime evidence that the US military is trying to gain 'first strike' potential over the USSR, so that it can destroy so many ICBMs at once that no response would be possible except a telegram of surrender.

Further evidence of this is provided by the US Navy's new Seasat system, which allows frequent measurements of the sea state – winds, waves, tides, currents, storms and so on – which is essential information for ensuring that Soviet nuclear submarines can be kept in view.

The science of geodetics deals with the exact shape of the Earth and its magnetic and gravitational fields. A number of satellites have been launched by the USA and the USSR to be observed simultaneously from Europe and America, allowing the exact distance between the continents to be determined precisely and the Earth's gravitational field to be mapped, again mainly to help with tasks like guiding missiles and navigating nuclear submarines. Dozens of geodetic satellites have been launched and in the early days

of the space age many observations of them were made by amateurs who had no idea that they were contributing to accurate aiming of nuclear weapons These amateurs – now mainly replaced by ground stations listening to transmitters in satellites gave the most exact data ever obtained on the Earth and its gravity field. In 1944 German rockets found it a task to hit London – now a missile launched in Soviet Asia could be targeted to strike whichever end of the Palace of Westminster its aimer chose.

A vast range of warlike activities, probably involving tens of thousands of skilled people in activities ranging from spacecraft manufacture to photograph analysis, already goes on in space. The complex systems for communication, surveillance and other purposes which are being set up there might not seem to leave much scope for enhancement But the constant expansion in military spending means that more and more money is available for the military exploitation of space Ideas being followed up by the US Air Force for the military use of space included $1.5 billion worth of projects for the USAF's Space and Missiles Systems Organisation, SAMSO. Some of the ideas may not be realised until the late 1980s or later.

According to SAMSO's commander, Lt Gen Richard C. Henry, 'SAMSO and NASA are looking jointly at various space system concepts envisioned during the next several decades'. In *Aviation Week and Space Technology* for 29 January 1979, he said that several of these would involve fabricating massive structures kilometres across in earth orbit. One would be a 'battle management' system involving an antenna up to 4 km across. This could provide every soldier in a ground army with his or her position to within 50 metres, provided they were equipped with a suitable wrist receiver. The positions would be found by measuring the difference between two radio signals at different wavelengths sent out by the satellite, which is capable of giving a unique position on the Earth's surface.

Another massive communications project under consideration is a 300 metre antenna which would be powerful enough to offer 1000 wrist radio communications bands. The system would find natural uses in espionage and by battlefield commanders. There might also be a 60 metre

antenna designed to provide 100,000 voice channels. According to Henry this could serve 'millions of users over a 1600 kilometre diameter area of the Earth's surface'. Other military satellites might be used to control remotely piloted vehicles, small unmanned aircraft which many armed forces are planning to use. Another communications system, which SAMSO plans to test in space in 1981, is a laser communications system for satellite to satellite communications which could be used in building large military data networks in space.

A 50 kg test satellite for this lasercom system is being built by the McDonnell Douglas Astronautics Company in the USA. And further in the future, according to SAMSO's thinking, there could be space telescopes with lenses of up to 600 metres diameter, suitable for a vast range of surveillance tasks on Earth and in space. This would provide the US military with a closer than ever look at its problems, and would collect so much light that it could see great detail even at night.

The arms race is being actively fought out in space by the USA and the USSR. They have the financial resources, and the personnel, to make military space programmes possible, and they have the global interests which make them worthwhile. But the amount of effort they are putting into the military uses of space has encouraged smaller-scale imitation. Other developed nations like France and the UK have launched military satellites in an attempt to break the superpowers' monopoly of the military possibilities of space, especially in terms of communications, or so the argument runs. The analogy to small countries' reasons for acquiring nuclear weapons is close. In addition, the USA and the USSR can both use military facilities in space to force smaller countries into alliances. This is part of the reasoning behind the USA's launching of satellites on behalf of NATO.

Neither the British nor the French space programme is large enough to provide independence from the USA, especially because the UK's satellites are launched by NASA. Perhaps the development of the European Space Agency's Ariane launcher will provide a higher degree of self-reliance for Europe's military satellites. And at the

moment, neither programme is large enough to provide the country it serves with a complete service British weather forecasts use many US photographs and other pieces of information for military and civilian purposes.

A more interesting case is that of China, which until recently has been independent of all other countries technologically and has developed its own rockets, rocket fuels, controls and other equipment for its space programme. Despite all these disadvantages, which recent contact with the ESA may alleviate, the Chinese launched two possible military satellites – China 4 and 7 in 1975 and 1976 as part of a programme aimed at developing reconnaissance from space. Both satellites are thought to have returned data capsules to China.

Another self help enterprise which achieved considerable notoriety in 1978 and which may point the way to future developments in Africa, Latin America and elsewhere is the case of Orbital Transport and Raketen, AG, OTRAG. This firm was set up in 1974 by a West German entrepreneur, Lutz Kayser, and obtained a lease, to run until the year 2000 on a 100,000 square kilometre patch of scrub and desert, later dubbed a test range, in Zaire. Rocket experiments began. The USA and the USSR both took OTRAG seriously enough to take a close look at it by satellite, of course. Although the scheme was at one stage said to be simply a tax-loss dodge for well-off Germans, it seems that attempts are continuing to make a usable launcher which can put satellites into orbit for Third World countries, which could use them for surveillance or communications, either military or civilian.

Critics of OTRAG and Dr Kayser think that the idea behind OTRAG's launcher many small rocket launchers instead of a few large ones in more usual boosters - will cause more problems than it solves, although some success has been achieved in tests so far. In addition, OTRAG has been forced to move away from Zaire because it has incurred President Nobutu's displeasure; Brazil is tipped for its next home. But unless by some vast political reversal, American and Soviet rocketry suddenly becomes available to the Third World, initiatives like OTRAG are likely to become more common.

KNOWN AND POSSIBLE MILITARY SATELLITE LAUNCHES TO END 1976

Type	*USA*	*USSR*	*Others*	*Total*
Photographic reconnaissance	224	363	2	589
Electronic reconnaissance	76	93	0	169
Early warning	36	9	0	45
Ocean surveillance	4	14	0	18
Navigation	31	25	0	56
Communications	100	206	9	315
Meteorology	61	53	2	116
Geodetic	19	14	5	38
Interceptor/ destructors	0	23	0	23
FOBS	0	17	0	17
Total	551	817	18	1386

Source: SIPRI

THE STATE OF PLAY ON PARTICLE BEAM WEAPONS IN SPRING 1979

Source. Scientific American April 1979

LOCATION OF ACCELERATOR	MAXIMUM ENERGY (MEV)	MAXIMUM CURRENT (AMPERES)	DURATION OF PULSES (NANOSECONDS)	REPETITION RATE OF PULSES
STANFORD LINEAR ACCELERATOR CENTER	20,000	.00003	2500	360 PER SECOND
SACLAY NUCLEAR RESEARCH CENTER	600	0002	1000	1000 PER SECOND
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	400	.0001	1500	1000 PER SECOND
UNIVERSITY OF GLASGOW	130	.0003	3500	240 PER SECOND
SANDIA LABORATORIES	1 5	4,500,000	80	3 PER DAY
HARRY DIAMOND LABORATORY	1.5	400,000	120	1 PER DAY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY	1 6	20,000	30	5 PER HOUR
SANDIA LABORATORIES	.35	30,000	30	100 PER SECOND

PROPERTIES OF PARTICLE-BEAM ACCELERATORS in existence today serve as a bas s for grouping these experimental dev ces into two broad categories high-energy, low current machines (*top*) and low energy, high current machines (*bottom*). An accelerator capable of generating a beam of neutral hydrogen atoms sJitab e for a satell te-based ABM system would reqJire a beam energy of 200 million electron volts (MeV), a current of between one ampere and 10 amperes, a pulse duration of 1 second and a pulse-repetition rate of several pulses per second An e ectron-beam accelerator for use against cru se miss les n the atmosphere would have to be capab.e of generating a beam with an energy of 500 MeV, a current of 5000 amperes, a pulse duration of 100 nanoseconds and a repet.tion rate of 10,000 pu ses per second

6 Science

Space was being used as a scientific laboratory long before there were scientific satellites. In the 1950s, high-flying aircraft and balloons were used to do scientific experiments at the boundary between the atmosphere and space. And rockets were being used for short flights into space before satellites were put there. Many interesting aspects of the universe which can only be seen from space – for instance, X ray stars, whose rays are prevented by the atmosphere from reaching ground level – were discovered first by rockets. Only later were X-ray astronomy satellites launched to take a more detailed look at the sky as it appears at X-ray wavelengths. Although rockets and balloons are still valued astronomical tools, the falling cost of satellites, and the fact that they can provide a stable and long term platform for scientific experiments means that scientific satellites are now doing most of the science done in space, a trend which is likely to continue.

The range of scientific experiments carried out already in space reflects almost the whole of science practised on Earth, from physics and biology to astronomy and all the Earth sciences. Many space experiments in fields like metal processing have been directed towards finding out whether industrial processes can be carried out in space. Others, like electron beam experiments, have had to do with spacecraft propulsion or possible weapons. And many of the earth observations made from space have been for commercial use – minerals exploration, crop analysis or weather forecasting, for instance. All these are explored in other parts of this book, here we are concerned with science which is not, at least yet, applied, including astronomy, the earth sciences, and studies of biology in the unnatural conditions of weightlessness.

Astronomy is the science most changed by the possi-

bilities of space. That is no surprise, since on one practical definition, astronomy begins where space starts. Astronomy is big science, like particle physics It involves huge telescopes rather as particle physics uses accelerators, and like particle physics, needs copious doses of computing to make sense of the observations. Despite this and the fact that every culture known to anthropologists has taken at least some interest in astronomy, in some cases making it the centre of whole cultures the Earth is a pretty poor place to do astronomy This may explain why western culture took until the seventeenth century to even discover the main facts about the structure of the solar system, with the planets – including the Earth in orbits around the Sun It was only the development of the telescope at that time, and later the discovery of photography and of the spectrograph – to allow the chemical composition of astronomical bodies to be examined which allowed the general structure of the universe to be described. In the case of the planets, only rough details of their surfaces can be distinguished from the Earth's surface, although it is possible to make a precise determination of the details of a planet's orbit from earth-based observations, and to find the mass of a planet which has satellites.

Before the start of astronomy from space, astronomy at optical wavelengths seemed to be approaching its theoretical and practical limits, since there is no sense in building telescopes much larger than already exist on the Earth's surface. The atmosphere's turbulence means that there are limits to how much a telescope can see from the Earth's surface. In radio wavelengths – where radio astronomy grew out of the 1930s discovery that objects in the sky, especially the Sun, emit radio waves in wavelengths which can get through the atmosphere to the Earth's surface – too, the possibilities are limited at the Earth's surface. This is partly because there are few frequency 'windows' in the Earth's atmosphere which allow radio waves through, and partly because manmade radio signals get in the way nowadays, including transmissions to and from satellites.

The disadvantages of operating at the Earth's surface mean that astronomers have had to site optical telescopes at remote, high sites – to get away from atmospheric

turbulence and the bright lights of civilisation. And quiet valleys free from radio interference are in demand for radio telescopes as well as for satellite ground stations. Although radio astronomers have had some success in having radio frequencies earmarked for radio astronomers which in effect rules them out for any other human use – both they and the optical astronomers, in search of new wavelengths and clear skies, are going to be making more and more observations from orbit and from deep space as time goes on.

Astronomy from space has, over the last 20 years, given rise to all the rich discoveries one would expect from a completely new way of looking at the Universe. Infrared and ultraviolet light have both been involved, these are types of light having wavelengths longer than the red end of the spectrum and shorter than the blue end. So have X-rays, and gamma rays, energetic radiation with wavelengths even shorter than ultraviolet light. Although infrared radiation from space can be detected at the Earth's surface, the task is much easier in orbit. None of the other wavelengths mentioned get through at all, so that space makes feasible several new types of astronomy in which the observable wavelengths increase from the millimetre up to which infrared observations extend, down to the thousand million millionth of a metre of the shortest gamma ray observations. Beyond the longest infrared light lie the radio wavelengths. Although so far radio astronomers have not made great use of space, the experiments they have made may lead to much greater things.

Working along the spectrum from the largest infrared radiation to the shortest gamma rays takes us from the lowest to the highest energy radiation. So it allows us a continuous look at every sort of astronomical object and event. Infrared astronomy is perhaps the least well developed new astronomy in space. The first infrared astronomy satellite is due to be launched early in 1981. Called IRAS – yes, Infrared Astronomy Satellite – it was being built at the time of writing as a joint venture between the USA, the UK and Holland, and was due to be used for infrared observations jointly with earth-based infrared telescopes. These are now numerous. There is even one at

Queen Mary College in central London, although most of them are deliberately sited at great altitudes, since the component of the Earth's atmosphere which cuts out infrared light is water vapour, which can be avoided by going to high altitudes. For this reason, the world's two biggest infrared telescopes are at the summit of Mauna Kea, a volcano on Hawaii, 4200 m above sea level. One is operated by the National Aeronautics and Space Administration, and the other by the United Kingdom's Science Research Council.

The combination of telescopes and satellite should make it possible to produce a complete map of the sky in infrared light, with IRAS operating in the whole range from eight to 120 millionths of a metre wavelengths. It will be able to operate at higher wavelengths than the land-based telescopes at Mauna Kea, which even at their Hawaiian site find problems seeing anything at longer wavelengths than 40 millionths of a metre because of atmospheric water vapour.

Why is the infrared sky interesting? Without a proper look it is hard to tell, but according to Robert D. Gehrz and John A. Hackwell of the University of Wyoming – the operator of another, smaller, infrared telescope – there are immense possibilities. For instance, they say in *Sky and Telescope* Magazine for June 1978, 'Because very young and very old stars are often embedded in thick clouds of gas and cool dust, they must be studied using infrared techniques.' This is because infrared light is given off by cool bodies. So visible and ultraviolet light, given out by hot, young stars, is absorbed by gas and dust around them and sent on again in infrared wavelengths. In addition, old stars which have run out of the hydrogen fuel which keeps them going cool down and become visible mainly in infrared frequencies. One thing which old stars do is to drive the heavy atoms formed within them off, just like a boiling pan – this is the mechanism, along with catastrophic explosions of old stars, which spreads heavy atoms – anything other than hydrogen and helium – between the stars. Without it the Earth would not be here, and only infrared surveys, like one with rockets already carried out by the US Air Force, can allow us to find out about it.

The wavelengths shorter than optical light – ultraviolet, X-rays and gamma rays – all have a longer history of exploration from space than infrared. X-ray astronomy, in particular, has in recent years given astronomy some of its most exciting discoveries.

Ultraviolet astronomy offers the prospect of letting us look at very hot stars – although these can be seen in the blue wavelengths of optical light, they put out most of their energy in the ultraviolet. And more excitingly, it also offers a look at the large-scale composition of the universe. The early history of the universe – how much material it contained and how closely packed it was – is reflected in the amount of deuterium, a heavy form of hydrogen, present. This can best be found by measuring the effects on ultraviolet starlight of deuterium.

This means that a wide range of astronomers are interested in the ultraviolet sky. They finally started getting the close look they wanted in January 1978, when the International Ultraviolet Explorer, IUE, was launched no less than 15 years after the idea for an ultraviolet astronomy satellite was first floated. The scheme was first put by the UK to the then European Space Research Organisation in 1964. The idea was axed at least twice in Europe before becoming IUE and being carried out jointly by NASA, the European Space Agency, which provided the IUE solar power system and the UK's Science Research Council, which came up with the ultraviolet cameras.

So far, IUE has been a great success, having provided nearly 10,000 ultraviolet pictures of the universe by the end of 1979. Scientists from 17 countries had used IUE's array of a 450 mm ultraviolet telescope, two spectrographs for examining the energy distribution of the ultraviolet light, and a camera to record what each of the spectrographs observed. One operates in the 115-195 nanometre wave-band (a nanometre is a thousand millionth of a metre) and one between 185 nm and 335 nm.

Late in 1979, the IUE astronomy teams had carried out delicate measurements of the abundance of heavy elements in stars and their atmospheres. These are important to understanding what goes on inside stars and the processes which distribute heavy elements throughout the universe.

In addition, IUE was providing a powerful look at the 'interstellar medium', the mixture of dust, gas, electromagnetic fields and emptiness which fills the space between the stars. One nearby galaxy, the Greater Magellanic Cloud, seems from IUE to have an interstellar medium like that of our own galaxy, with graphite dust present. IUE has also looked at highly energetic galaxies like the Seyfert galaxies, which are rich in interstellar dust.

Another object outside our own galaxy viewed by IUE is a supernova, the explosive last stage in the life of some stars. Only a few of these have ever been observed in our galaxy, but they are so bright that the April 1979 one was visible from the 100 million light years distance of the Messier 100 galaxy where it happened. At that distance, individual stars are usually invisible. With IUE, it was possible to watch the material ejected from the supernova as it was thrown away from the star and cooled down.

All these successful observations meant that IUE users and other ultraviolet astronomers had begun by mid-1979 to plan the next generation of ultraviolet observatories. One plan is called EXUV, and involves a combined X-ray and ultraviolet satellite, using two telescopes. IUE was placed in a geostationary orbit over the Atlantic, with control shared between Europe and the USA, so that it could be used essentially as an ultraviolet telescope on the Earth's equator. That has the disadvantage that it is not possible to get much of a view of the ultraviolet sky at high latitudes. The EXUV satellite, if it goes ahead, may be placed in an orbit with a steep inclination to the equator, allowing it to be used to make a complete ultraviolet and X-ray survey of the sky.

The boundary between ultraviolet light and X-rays is usually set at a wavelength of about a nanometre. X-ray astronomy is, again, quite impossible from the Earth's surface, and had its origin in rocket flights which painstakingly found small numbers of X-ray sources. Although there were plenty of exciting moments in this sort of research – the best, perhaps, where one bright X-ray source was found to be the remnant of a supernova observed from China and elsewhere in 1054 – it is not

possible to carry out systematic experiments or surveys from rockets which allow just a few minutes' look at the X-ray sky. For this, satellites are needed there have by now been a good number dedicated to X-ray astronomy.

An early idea of the potential of X-ray and ultraviolet astronomy was obtained by the US Orbiting Astronomical Observatory series, which consisted of the two successful satellites and two failures. OAO 2 and 3, the successes, were launched in 1968 and 1972, and proved the viability of putting telescopes which need accurate pointing mechanisms if they are to give usable results – on unmanned satellites. OAO 2, for example, allowed information to be obtained on the ultraviolet brightness of CW Cephei, a 'variable star' whose output of visible light has long been known to fluctuate. It was armed with no fewer than 11 telescopes operating in various wavelengths. OAO 3, launched in 1972, had an ultraviolet telescope and three X-ray ones. Here the aim of the X-ray telescopes was systematic, involving a close look at known X-ray sources and a search for new ones.

The OAO experiments were so successful that a follow-up series – the High Energy Astronomical Observatories were planned, and began in 1977 with Heao 1, much delayed by NASA budget cuts. Heao 1 was able, from an inclined orbit, to provide a complete survey of the X-ray sky with objects shown to within about half a degree, about the size of the full Moon in the sky. It was followed up in November 1978 by Heao 2 – Einstein as it was called, in honour of the physicist's centenary in 1979. Even before Einstein was launched, over 1000 celestial X-ray sources were known. So Einstein was designed to go for high resolution. With the close look Einstein was able to give them, astronomers realised that many stars or perhaps more likely, their atmospheres – give out X-rays in quantity. And – in a series of observations which achieved wide publicity – Einstein undertook measurements of X-rays from what may be the most distant objects in the observable universe, called Quasars, with the aim of finding out from their brightness how much material lies between them and us in the universe. This is of interest because it can tell us how much mass there is in the universe

and therefore how strongly the different galaxies within it are attracted to each other. It has been known for most of this century that the universe is expanding, but the gravitational forces which tend to slow down the galaxies' headlong rush apart are less well known As this is being written, it looks as though large amounts of extra mass have indeed been run to Earth, as it were, by Heao 2, so that some time the universe may start contracting again It is too early to be sure, but without space observatories it would most likely be impossible even to ask the question

X-ray astronomy is a highly international science. Many non-US researchers have used Heao 2, for instance Many other countries have also produced X-ray satellites including Holland with ANS (Astronomical Netherlands Satellite), India with its Bhaskara satellite, and the UK with Ariel V and VI. At a UK Science Research Council celebration in November 1979, held to mark five years of successful operation of Ariel V, it was stated that the satellite has redrawn earlier X-ray sky maps (important because the X-ray sky changes more rapidly than the visible one) as well as examining bright X-ray sources mainly other galaxies – in exceptional detail. And the politics cannot be ignored - British astronomers had been kept at the forefront of the field and British contractors and satellite ground controllers had been shown worthy of participating in further scientific satellite schemes. One discovery which Ariel V may have made, it was thought in July 1979, was a dark mass of anything up to ten times the mass of the biggest known things in the universe so far, which are large clusters of galaxies. This huge and distant object may be needed to account for the flux of X-rays observed by Ariel V.

With a success of that size on its hands, it is no wonder that the SRC decided that Ariel VI, the successor to Ariel V, should be another X-ray satellite. It was launched in June 1979, carrying more experiments from British universities, including one designed to measure not X-rays but cosmic rays, atomic particles produced by the Sun and other stars which - although they can sometimes reach the Earth's surface – are best studied from space, especially the comparatively rare heavier particles which the Ariel VI

experiment provided by Bristol University was designed to examine.

The UK is not alone in thinking that X-ray astronomy has a big future. The European Space Agency plans another X-ray satellite, Exosat, for a November 1981 launch at the earliest. Dutch, British, Italian and German researchers are involved in the project.

Even shorter wavelength astronomy – looking at even more energetic phenomena than X-ray astronomy – has also come into its own, mainly through a single satellite called Cos-B, launched in 1975 for ESA by the Americans. Shorter wavelengths than X rays take us into gamma rays, and Cos-B detected its first celestial gamma ray source within a week of being launched. One galaxy previously observed in radio wavelengths was seen, as were several objects within this galaxy. The ultimate targets for gamma ray astronomy could be sexy indeed – perhaps even the 'big bang' which started our universe off has left a trace in the gamma ray background, there could also be a payoff for high energy physics. Less dramatic prospects, like examining the composition of the planets, also exist, and could make all the difference to getting the budgets in times when comparatively applied research seems like a better bet than discovering where the universe came from. Another gamma ray observatory is the latest Heao, Heao 3, launched in 1979. Like Ariel VI, Heao 3 looks at cosmic rays as well and seems to be working well despite surviving Hurricane David while on top of its Atlas-Centaur rocket at Cape Canaveral waiting to be launched. French gamma ray experiments are also being flown, on Soviet Prognoz satellites which carry both French, East European and Russian experiments.

All this is very interesting for astronomers and not very expensive for the rest of us (about $44 million, £22 million for Heao 3, for instance.) But although there are some high points in which the rest of humanity sometimes takes an interest, most people only get interested when a spacecraft actually makes the big trip to a nearby planet and tells us, spectacularly, what it looks like and consists of. Although a manned voyage is the most spectacular, this book will probably be out of print before the first man, much less the

first woman, gets to Mars. That means that the planets of the solar system will continue to be explored by robot machinery, which has already revolutionised our ideas about them.

Until the space age, our knowledge of the planets was pretty thin. What was known had been found out by astronomers looking down telescopes or attaching cameras to them. Since it has become possible to send space probes to them, the amount of information available about the planets has increased by billions of times. The first spacecraft flybys of Jupiter and Saturn in the 1970s, for instance, told us much more about them than every astronomer back to Galileo had found out. And, perversely enough, the astronomers themselves have more or less been muscled out of the field by specialists in the Earth sciences geologists, geophysicists, meteorologists and even biologists, all keen for a new planet with which to make the comparisons with Earth. Only the biologists have so far failed to find anything definite to compare.

The planetary probes are a new dimension in astronomy for another reason, too Until they began, astronomy had always been a science without experiments. Astronomers had not been able to do what every other scientist from agronomists to zoologists does – carry out experiments to eliminate wrong ideas. Instead of experiments, all they had been able to carry out had been observations, by ever more sophisticated methods. With space probes, all that changed. Instead of looking at Mars through a telescope or wondering whether the spectrum of its green patches means that plant life is present, it is possible to send a spacecraft to the place to dig up some soil and incubate it several ways to see whether anything in it is alive. So planetary astronomy has been expanded in all ways by the space age the amount of information has ballooned, the scope for experiment has widened beyond measure, and the ties to other sciences, especially those developed to understand the Earth, have been strengthened.

Voyages to the planets began in 1959, with the Luna spacecraft from the USSR. The Luna craft, and their US rivals - this was during the 'space race' at its height, and the term is fully justified – were part of what geologist Bevan

M French calls 'the look before the leap' in his *Moon Book*. Although only Americans have so far made the leap to the Moon, Soviet and American space probes have both been there and there may be a European Moon explorer in the 1980s. In addition, US and Soviet probes have visited Mercury, Venus and Mars, the rocky Earth-like planets nearest the Sun – Mars outside the Earth's orbit and the other two within it, and Jupiter and Saturn, the first two giant gassy planets beyond Mars. Uranus, the seventh planet of the Solar System, is due to receive a visit in 1986.

Results from interplanetary probes have been filling up scientific journals for twenty years, and the technology which goes into them is among the most formidable known. The first Moon probes were simple kamikaze craft, crashing into the Moon uncontrolled, taking photographs all the way in. In contrast, the latest planetary spacecraft have been sophisticated enough to give biologists pause for thought. In The *Dragons of Eden*, Carl Sagan – a biologist who has specialised in the possibilities of life on other planets – says that the computer in the Viking Mars lander was so complex that one could not be sure how it would respond to a given signal, and says 'We begin to wonder if it is truly intelligent.' The falling weight, and power requirements, of computers means that more and more machine brainpower, up to and including what is called, with increasing confidence, artificial intelligence, is going to be on board future spacecraft. Maybe man won't feel the need to go at all.

It isn't possible to detail everything there is to know about interplanetary spacecraft or what they can tell us about the solar system. But we can talk about the sort of problem they help illuminate. In a way, the technology is the easy part. Interplanetary explorers are launched in the same way as any other spacecraft – by rocket, with the space Shuttle and its competitors likely to assume a role in the future. And because they spend all – or, in the case of surface-landing craft, most – of their time in space, they look rather like Earth satellites. The differences are subtle but radical. For instance, they are equipped with finely-tuned navigating equipment, designed to allow them to catch a moving target after a year's long flight. They also

have more communications capability than many Earth satellites, since they have to communicate everything from temperature measurements to colour photography across millions of kilometres. The signals are typically down to thousandths of a billionth of a watt before being pulled in by big receivers on the Earth. Once a thunderstorm in Australia meant the complete loss of data from Mars being received at a tracking station there. And because spacecraft cannot be sent to the planets often or in great number, they typically carry large numbers of experiments.

So how much has 20 years of missions to the planets told us? In the case of the Moon, the first planet to be invaded and the most often visited, the answer must be that every question that could sensibly be answered by surface exploration has been In time, the same answer will apply, too, to the other rocky planets and perhaps, ultimately, to the gas giants – Jupiter and its kin – as well, so it is worth looking closely at what we have found out about the Moon. It seems that apart from the big questions like where it came from and what lies at its centre – which could not be well answered even about the Earth – most of the mystery has been taken out of the Moon.

Although French calls the unmanned missions the look before the leap, he would also admit, like many another lunar scientist, that the look and leap each had a vital role in telling us what the Moon is like and how it got that way. The earliest Moon probes the Soviet Lunas and the US Rangers – were the first advance since the invention of the telescope in our view of the Moon. (One of them Luna 3 – made a trip round the side of the Moon kept permanently invisible from the Earth.) The Moon rotates on its axis once each time it orbits the Earth, so that we can only see one of its two faces. So Luna 3 gave us our first look at the Moon's hidden side, although the pictures it returned were unreliable and do not form the basis of the maps of the invisible hemisphere of the Moon which are now in use.

The Ranger programme was something of a fiasco to start with – Rangers 1 to 6 all ended without a single picture of the Moon being brought back, for one reason or another, before Rangers 7, 8 and 9 paid rich dividends, a total of over 17,000 pictures showing details of the lunar

surface down to a few metres across. The Rangers worked by being pointed at what promised to be an interesting part of the Moon and accelerating towards it, eventually crashing, as it turned out, no more than 30 km from the intended target in the successful missions. The Rangers told us that the Moon's most obvious features – craters – exist in even greater numbers down to the smallest sizes. When Moonrock finally became available, it was apparent that even on the smallest scale, the Moon is a mass of craters. The reasons for this are related intimately to the big facts about the Moon's history. The craters are caused by the Moon's almost complete lack of atmosphere, which in turn means that even the smallest meteoroids, microscopic particles in orbit around the Sun, reach its surface unimpeded. When they approach the Earth they are stopped by its atmosphere.

The big meteorite impact craters do have Earthly equivalents, but they are hard to find. The largest craters of the Moon are called Seas – Maria in Latin – which are large flat plains, formed when the Moon – which, like the Earth, is just over four and a half billion years ago – was young. In those days, the solar system still contained large 'planetismals', masses hundreds of kilometres in diameter which amalgamated to form the planets. The impact which greeted their merger with the rest of the Moon left huge craters filled with liquid lava, which became the Maria. The same scars must have been visible at the same time on the Earth, but they have long been removed by the Earth's much greater geological activity. The Moon is small and cool, and the signs of internally-caused geological activity on the Moon are minor. On the Earth, meteorite craters are hard to find compared to features caused by the Earth's own internal activity, and by erosion caused by the Earth's winds, rivers, seas and glaciers.

All this could have been surmised before visits were made to the Moon by man and machine. The fact that it was not has at least as much to do with the small amount of work which had been done on comparisons of terrestrial meteorite and volcano craters before Ranger. But the full image of the Moon could only be drawn with the aid of two highly successful Moon missions. The first, Lunar Orbiter,

used five spacecraft -- they all worked perfectly -- to make a precise survey of over 95 per cent of the Moon's surface, front and back. Thousands of photographs, a thorough analysis of which is still not complete, were taken, showing detail down to just a few metres across. The other was the most spectacular thing so far in space exploration, Apollo, a series of space shots, which, from Apollo 11 to 17 – except for the near-disaster with number 13 – brought back 387 kg of rock and soil from both main types of lunar area, the seas of solidified lava and the old uplands where rock shattered in meteorite explosions is dominant.

These US missions should not divert attention completely away from Soviet Moon exploration, which has so far used only robots to explore the Moon's surface. Many US critics of the Apollo programme thought that men were, in any case, going to the Moon for prestige, politics and public relations instead of science. The highlights of the Soviet Moon programme so far have been Luna 16 and 17, both put on the Moon in 1970, the year after Apollo 11. Luna 16 succeeded in blasting off from the lunar surface and returning 100 grammes of lunar surface materials – rock and soil – to the Earth. Luna 17 took Lunakhod 1, a mobile robot, to the Moon, in its way at least as impressive as the self-drive Moon Buggy used by the later Apollo astronauts for lunar excursions. All this was a follow-up to the first soft landing on the Moon, made by Luna 9 in 1966, several months before Surveyor 1, the USA's first lunar lander. Luna 9 sent back the first pictures from the Moon's surface. The two Lunakhods – unmanned lunar vehicles, carrying scientific experiments, and controlled by a five-man crew in the USSR watching progress by live TV – were as spectacular a success as the moon-samples returned to Earth, putting in nearly 50 km of Moon distance, returning tens of thousands of photographs and in the case of Lunakhod 1 – landed by Luna 17 – operating for no less than 11 months. The Lunakhods – number 2 was landed by Luna 21 early in 1973 – were able to stay active on the Moon longer than men could and carry out experiments at leisure, as well as carrying with them analytical equipment to do more real science on the spot than Apollo could.

Critics of Apollo said that a programme of orbiting

spacecraft to take detailed photographs of the surface – and to examine gross characteristics like its weak magnetic field and its interesting gravity field – along with robot explorers to look at the small scale properties of rocks and perhaps return them to Earth, could have found out at least as much as manned exploration, and more cheaply. It is not possible to decide if they were right. And Apollo obviously provided a massive boost to manned spaceflight, giving wings, for instance, to the space shuttle idea. But if both manned and unmanned spaceflight are important in their own way, it is interesting to compare our knowledge of the Moon with that of Mars, the next planet from the Sun after the Earth, which has been visited only by machines. The answer, it seems, is that without having Mars rock available to earthly laboratories, we have learnt a lot about the place.

Before spacecraft went there, telescopic observation had revealed that Mars is smaller than the Earth – about half its size – and lighter, with about one third of its surface gravity. It had also established the existence of two very small satellites, Phobos and Deimos, and produced a large and inconclusive mass of observations of the Martian surface, including the famous canals of Mars mapped by Percival Lowell, who thought them to be irrigation canals. The 'canals' were later proven to be largely optical illusions. The telescope had also shown that the red planet had polar caps something like the Earth's – although of unknown composition – and an atmosphere with clouds.

Spacecraft began looking at Mars – after some false starts like the Soviet Mars 1 – in 1964 with Mariner 4, which failed to show any signs of intelligent life but, instead, revealed a cratered landscape for which 'lunar' was the inevitable adjective. It also seemed that any Martian magnetic field was weak, that there was little if any upper layer of charged particles like the Earth's Van Allen belts, and that the atmosphere was thin. Later Mariners – 6 and 7 took many more pictures and showed that the Martian atmosphere consists mainly of carbon dioxide. They also showed that Mars looked geologically active, forming a kind of half-way between the Earth and the Moon. Cratered country exists, and so do many valleys, moun-

tains and other features which have to have been produced by geological action.

In 1971, another Mariner altered our knowledge of Mars fundamentally. This was Mariner 9, the first Mars orbiter, intended as part of a two-spacecraft shot at Mars Mariner 8 ended up, instead, at the bottom of the Atlantic. After several frustrating months in which the Martian surface was completely obscured by a dust storm, Mariner 9 began to return faultless photography of most of the planet to Earth. The view was astounding, including valleys in which the Grand Canyon could readily be lost and volcanoes which could scarcely employ Vesuvius as a a foothill. The picture of Mars which emerges from all this is an active one; like the Moon, Mars is heavily cratered – indeed, the ages of different parts of the Martian surface are calculated by counting the craters. The more there are, the longer the area has been exposed to the meteorite rain from the sky. Erosion on Earth is so fast that that technique could not be used even if it were needed. But although meteorite craters are there, they are less striking on most parts of the Martian surface than evidence of water erosion - the valleys – and geological activity from within – the volcanoes. And although there is not now much sign of water, there is plenty of evidence of an active atmosphere which must still be altering the surface for instance, the dust storm which greeted Mariner 8.

This was a momentous curtain-raiser for soft landings on Mars, first accomplished in July 1976 by Viking 1, joined in September by Viking 2. The Vikings – a third has been mothballed by NASA for lack of money to launch and operate its mission – come in two parts, an orbiter and a soft-landing spacecraft which descends from it to the surface. It is the landers which have produced the most spectacular results including observations of Martian earthquakes – the term Marsquake is too ugly to use and some enigmatic results from the biology detectors which probably do not demonstrate the presence of life but which gave the Viking biology teams some exciting moments. The orbiting satellites have also done important work, demonstrating for instance, the presence of water ice in the Martian clouds and other details of Martian meteorology.

The lander pictures look like nothing so much as one of the less friendly parts of the Sahara desert, showing that wind is the force which does most to shape the Martian surface on a small scale These tie in well with Viking Orbiter pictures, and earlier photographs from Mariner, which show areas of large-scale sand and rock features similar to landscapes familiar from Earthly deserts

The huge amounts of information brought in by Mariner and Viking cannot be taken in comprehensively in a book which is primarily about space It would be surprising if they could, since the number of US and Soviet space probes which have been there is in double figures But it does not take much of a space programme to increase vastly our knowledge of even apparently familiar planets An example is Mercury, a Mars-like world which is the nearest planet to the Sun, taking only 88 days to our 365 to orbit around it. Until the 1960s it was thought, for instance, that Mercury's day and year were both 88 days long Observations of its surface markings were co ordinated on this basis to produce a map of what was thought to be Mercury's illuminated hemisphere It was thought that Mercury must contain the hottest areas in the solar system on its sunlit hemisphere, and the coldest on the half which the Sun never reached. Radar observation eventually revealed that this view was baseless. In fact Mercury rotates on its axis three times every two Mercurian years, giving a 59 day rotation period So about a decade before the first spacecraft arrived at Mercury, centuries of telescopic observation, which had produced maps dotted with resounding sounding places like Solitudo Hermes Trimegisti, were shown to have been largely in vain (The maps are not completely wrong - Earthly observers usually see the same face of Mercury, which is the source of the confusion.) Mercury is difficult to observe because it is rarely seen in a fully dark night sky, since its orbit is close in to the Sun It remained a planet of mysterious dark markings and possibly a tenuous atmosphere until 1974 and Mariner 10. This US spacecraft, like later missions to Jupiter, Saturn and Uranus, got to Mercury by taking a boost from another planet's gravity field, in Mariner 10's case that of Venus Venus is by now well-visited by space

probes, but Mariner 10 was the first to make the journey on to Mercury.

Mariner 10 made a total of three passes of Mercury, in March and September 1974 and March 1975. These produced a total of some 10,000 photographs. Mariner 10 also carried magnetometers – which were also used during the flight to examine the interplanetary magnetic field – and thermocouples to measure the surface temperature of Mercury and Venus. Mariner also carried an ultraviolet wavelength spectrometer to detect any Mercurian atmosphere, since most gases have an effect on ultraviolet light.

The technique used to get Mariner 10 to Mercury has been well described by Arthur C. Clarke in the context of a mission to Saturn – in *2001*. The difference in the case of Mariner 10 is that it was done 'downhill' with the Sun's gravity pulling Mariner on instead of back. Mariner was launched from the Earth into an elliptical orbit round the Sun designed to bring it into contact with Venus. It approached Venus from behind and was swung round the planet's face by Venus's own gravity, leaving Mariner on a more extreme elliptical path designed to bring it to Mercury. Mid-course corrections were necessary, using small thrusters, but Venus's gravity did most of the work. The same trick, worked this time with Mercury's own gravity field, ensured that not one but three rendezvous with Mercury. Mercury has a much less circular orbit than the Earth – it ranges from 45 to 70 million kilometres from the Sun, while the Earth is always about 150 million kilometres from the Sun.

Once at Mercury, Mariner 10 photographed just over half of the planet in its three passes. They revealed features down to about 100 m across, compared to the several hundred kilometres which is the best an Earth-based telescope can manage. Another Mariner 10 first – in addition to being the first space probe to use another planet's gravity to alter course – was that the pictures were transmitted back to Earth by live TV as they were taken. They revealed a pretty lunar world, with craters, valleys and escarpments reminiscent of the Moon's mountain country. (This author remembers picking up the American magazine *Sky and Telescope* at the time, looking at its cover

and thinking 'what a lovely crescent Moon' before realising that it was Mercury.) Not a lot of what Mariner showed us can be tied in with the painstaking telescopic maps, so a complete new nomenclature has been thought up, naming Mercurian craters and other features mainly for Earth musicians, artists and writers. Names like Mahler, Bach, Mozart, Purcell, Beethoven, Titian, Dickens and Turgenev appear, and their counterparts from other cultures all over the world. There are also, for instance, valleys named after the radio telescopes like Goldstone and Arecibo which brought home the Mercury 10 data.

If the Mercurian topography is lunar, the atmosphere is slightly more promising than the Moon's consisting of a very thin scraping of rare gases – helium, argon and neon – derived from the Sun. They appear, from observation of glows in the unlit part of Mercury, to give auroral displays. There is also a magnetic field, a few per cent as strong as the Earth's, which provides a vital clue to the inside of Mercury. It seems that Mercury consists almost entirely of an iron core, accounting for the great bulk of the planet's mass, and giving rise to its magnetic field. So although Mariner 10 cannot have solved all the questions about Mercury, it succeeded in answering many key questions about the planet's topography, atmosphere and and interior in just three passes, and virtually destroyed terrestrial telescopic observation of Mercury as a valid scientific activity.

In contrast to Mercury, Venus has been visited by space probes since 1961, when the USSR's Venus 1 passed close to the planet – unfortunately after a communications failure which meant that no data was returned. Between 1961 and 1975 Venus was the target for no fewer than 25 space probes, of which only 10 returned data. Venus seemed unkind to spacecraft despite being the most tempting planet available to mission planners. Venus is about the same size and weight as the Earth and, unlike the other inner members of the solar system except the Earth, has a very obvious atmosphere – so evident that the surface has probably never been seen from Earth. Instead, telescopic observers spend their time looking at markings in Venus's cloud layers and trying to analyse the clouds

with spectrometers. So until the advent of the space age, even basic parameters like the length of the Venusian day were unknown. That was finally discovered by Earth-based radar astronomy, which showed that Venus rotates once every 243 days, in a sense opposite to the rotation of the Earth, its own 225-day year and the direction of virtually every other astronomical movement in the solar system.

That state of ignorance was galling to astronomers, who had to make do with only the skimpiest data about what is at times the brightest thing in the sky after the Sun and Moon. The Venus probes between 1961 and 1975 filled in some of the yawning spaces, as did radar mapping of the surface. Mariner 10 — of Mercury fame — revealed, for instance, that the atmospheric layers pay little attention to the languid rotation of the solid planet, instead carrying out one rotation every four days at the top of the atmosphere, about 70 km above the surface, slowing to virtually nothing some 40 km below, at the base of the clouds. A year later, in June 1975, two Soviet spacecraft, Venus 9 and 10, succeeded in making the first soft landings on Venus, surviving about an hour at the surface before the heat and general inhospitality of the Venusian surface killed them off. On the way through the atmosphere they sent back data showing that the clouds probably consist mainly of sulphuric acid, diluted with some hydrochloric acid and other gases which, on Earth, are produced naturally only in small amounts from volcanoes. The surface itself is virtually dust-free, despite the expected heavy erosion from wind, and seems to be as rocky as the Moon or Mars. And there is quite a lot of light around at the surface, despite the thick clouds.

The Soviets followed up this success with Venus 11 and 12, again designed as Venus landers but this time accompanied by a clutch of US Venus explorers, including Pioneer Venus 1, the first Venus orbiter, and the US Venus multiprobe, a five-in-one spacecraft. That made a total of 10 spacecraft arriving in December 1978, since each of the Soviet craft had a flyby probe as well as a lander. Pioneer went into orbit successfully, and even succeeded in photographing the Venusian surface, in infrared light,

through what seems to be a gap in the clouds at the Venusian North Pole. The Pioneer concentrated on high-quality atmospheric information, including temperature maps of the atmosphere at different levels. The atmosphere seems comparatively simply – the layers of cloud which absorb most energy from the Sun, or reflected back from the planet's surface, are the ones which have the most extreme winds, which is what would be expected. The orbiter also continued the work of mapping the surface in radar frequencies, showing up mountain ranges and volcanoes bigger than any on the Earth. Although the Orbiter was the star of 1979's Venus investigations, its observations were backed up by those from the multiprobe and the Venus 11 and 12 landers. For instance, the Orbiter observed lightning and the landers heard thunder. The US multiprobes which entered the atmosphere successfully confirmed and added to early observations of high wind speeds in Venus's upper atmosphere, with speeds of 640 km per hour at 55 km, in the high clouds, and only 16 km at the surface. With four Soviet landers now having returned data from Venus and the Pioneer spacecraft returning a flood of data from above the clouds, years of analysis lie ahead of Venus watchers. And more Venus probes are planned, including a joint Soviet-French one.

From cloud watching to science might also be the motto when it comes to looking at the other two solar system planets so far visited by space probes, Jupiter and Saturn. These are the two giants of the solar system with masses respectively 318 and 95 times that of the Earth. Neither is an easy target – their orbits are seven and thirteen times as far from the Sun as the Earth's – and they only began in the 1970s to yield some of their secrets to spacecraft. The two giants have now been visited by a clutch of spacecraft, beginning with Pioneer 10 and 11's visits to Jupiter in 1973 and 1974. Pioneer 11 has also flown by Saturn, as did Voyager 1 late in 1980, to be followed in 1981 by Voyager 2. And in 1986, Voyager 2 will begin the exploration of the outer planets, unknown before the invention of the telescope, Uranus, Neptune and Pluto, by flying past Uranus.

Jupiter is one of the most spectacular objects in the sky to

view with the telescope, and long before the Voyagers and Pioneers began to look at it, amateur and professional astronomers had accumulated decades of observations of its cloud surface. This is an ever changing panorama of belts, spots and other features, including the celebrated great red spot which seems to have existed, unlike most Jovian cloud features, for hundreds of years at least Later on, radio astronomy had confirmed that Jupiter, as befits a world dominated by clouds and called after the King of the Gods, has thunderstorms on a gargantuan scale, and that it gives out into space massively more radiation than it receives from the Sun, so that the ever-changing cloudscape must conceal an active interior.

The Pioneers showed that atmospheric convection is the main mechanism which makes Jupiter look like it does Its detailed photography including pictures of the polar regions, which are all but invisible from Earth, showed that the cloud patterns can best be explained by taking account of both heat from the Sun and heat from Jupiter's own interior, as well as the forces set up by Jupiter's own rotation of less than ten hours – pretty rapid for a body with hundreds of times the Earth's mass. Some astronomers, indeed, think that Jupiter is at least part-way to being a star. It emits radiation while other planets, except Saturn, just absorb it from the Sun, it has a mass more than thrice that of Saturn, its nearest rival in the solar system, and it has accumulated most of the solar system's angular momentum outside the Sun, as its short day shows. It also has in common with Saturn – its own miniature solar system in tow, in the shape of at least 14 satellites

The Voyager 1 and 2 flybys revealed a wealth of data about the satellites as well as more information about the planet itself. They photographed, for instance, what may well be the first active volcanoes observed in another world, on Jupiter's satellite Io. These may be sulphur volcanoes emitting plumes of sulphur dioxide rather than the silicate lava found coming out of earthly volcanoes. The other Jovian moons discovered by Galileo seem equally odd, providing in some ways a microcosm of the solar system; Callisto is a mass of craters, possibly meteoritic; Ganymede and Europa have icy, fractured surfaces, possibly covering

a rocky core, and there has been speculation about whether life might have arisen in the fissures

Space observations of Jupiter's magnetic field have reinforced the theory that its interior may consist largely of liquid hydrogen in a metallic form, whose convection gives rise to its magnetism This is much stronger than the Earth's, itself the strongest among the rocky planets Space observations – this time by Voyager 2 also discovered a fourteenth satellite of Jupiter, and the Voyagers also discovered a ring around Jupiter, like Saturn's but far weaker, not long after telescopic observation from Earth had proved the existence of a ring around Uranus. The discovery that rings once thought to be the sort of rarity which more alien species would travel to Saturn from other solar systems to marvel at – are in fact not unique even in the solar system, perhaps brings closer the day when we can finally say how they are formed.

Saturn itself has so far been visited only by Pioneer 11, although 1980 and 1981 should also see Voyagers 1 and 2 there as well. The Pioneer 11 flypast was scarcely a disappointment, with the discovery of a new ring outside the four seen with ground-based telescopes The Pioneer observations also sorted out the structure of the rings and the gaps between them, which are caused by the gravitational pull of Saturn's satellites, thus settling some long-standing feuds among astronomers Pioneer 11 also made the dangerous passage through Saturn's rings – which consist of rocky particles at a low density without damage, and found the eleventh and twelfth moons of Saturn, the other ten having been discovered telescopically. It also obtained data with photometers and other equipment to allow models of Saturn's atmosphere to be built up. As with Jupiter, the contribution of heat generated inside the planet is about twice as important as incoming sunlight. In Saturn's case, though, the internal engine driving the heat production must be even more compact than Jupiter's – not only is Saturn smaller, it also has a far lower density, less than that of water, so that it probably consists largely of gaseous hydrogen. So the answers to key questions about Saturn – and presumably Uranus and Neptune – may well be found by scaling down

from what can be discovered about Jupiter. Everything from the magnetic field again attributed to metallic liquid hydrogen, to the activity of the atmosphere seems to be the same but smaller. Only the rings are bigger and better.

As Carl Sagan put it in his bestseller *The Cosmic Connection* there can only be one generation for whom the planets are indistinct discs in their youth and familiar worlds in the course of being explored in their old age And we are that generation. Apart from the upcoming visit to Uranus by Voyager 2 in 1986, there are no new worlds to be looked at according to present space exploration plans. Instead, there are plans for detailed unmanned looks at planets which have already been visited by space probes. Budget problems make it seem improbable that the position reached by NASA in mid-1979 will be repeated soon: then NASA was tracking no fewer than 15 interplanetary space probes, including the Pioneer Orbiter at Venus, two Voyagers en route to Saturn, and a Viking Orbiter at Mars. But there are plans for a Jupiter orbiter, Galileo, although the scheme is stuck in the mud at the time of writing by delays in getting the space shuttle working and by NASA budget problems. The best date for launching Galileo is early 1983 if it gets later, the payload has to drop as Jupiter gets farther away. It was originally intended to launch Galileo jointly with the NASA European Space Agency Solar Polar Mission more of that later – but shuttle delays and cost overruns mean that the launch windows when Galileo could be launched best are slipping by. A 1984 launch would mean using a lot more power to drive Galileo to Jupiter; it will get there, if it goes at all, via a Mars flyby.

So far, the Soviet Union and the USA have had planetary exploration to themselves, although there are European Space Agency plans for lunar orbiting spacecraft and lunar landers, as precursors, perhaps, to orbiters for Mercury and Mars. The Americans are working on ideas like flights to return Mars rock samples, huge aircraft to fly in the Martian atmosphere, and a Mars rover. Budget cuts have meant that these are all being pursued with fewer staff and less chance of implementation than before.

Part of the reason for this is that mission costs are getting

higher all the time and except in an era of rapidly rising budgets, a constant number of flights cannot hope to be sustained. According to Thomas Bird and Ronald Sheahan of the Jet Propulsion Laboratory, the California Institute of Technology establishment which has carried out much key work on spacecraft design, the answer will probably be to make spacecraft cleverer. Launch costs are tumbling, it is managing the missions which cost money.

They pointed out in a 1979 issue of *Astronautics and Aeronautics* that the number of on-board processors – small computers to run the spacecraft – has gone from none for the Mariner flyby of Venus in 1967 to 17 for the planned Galileo spacecraft. This gives a better spacecraft – it can respond instantly to problems instead of waiting hours for an answer from Earth. This means an 'almost explosive growth in the sophistication of planetary spacecraft' which can give cheaper and better missions if used properly.

Another trend in solar system exploration is away from looking at planets and towards looking at space itself, and the smaller bodies which are to be found in it. Like asteroids – small rocky bodies ranging in size from a few hundred kilometres to tens of metres – and comets, which despite the imposing appearance of the bigger and better ones, actually have very little physical content. They only look impressive when, as they approach the Sun, sunlight makes them give off gases and particles which were previously frozen solid. The relation between comets, asteroids and other small bodies in the solar system has long been fascinating for astronomers. But it may, in the long term, have a real importance for mankind in general. The asteroids may eventually become a valuable natural resource, since they are very light, and material from them could be obtained with very little gravity to fight against. If space colonies are ever built, they might be built with asteroid stuff instead of Earth or Moon materials. So a small investment in a good look at the asteroids could eventually be money well spent.

Although there are NASA plans for exploring the asteroids – most of which have orbits between Mars and Jupiter, although many range much wider – it is the comets which may well receive the first mission designed to explore the solar system's small bodies. The prospect which appeals

to scientists is the opportunity of having a good look at the most famous comet of them all – Halley's – around the middle of this decade. So far, the scheme, which would also take in Comet Tempel 2, seems to have few attractions for the US Office of Management and Budget, which is involved because it has to approve the American end of the joint NASA/ESA scheme.

The full plan would involved both a flyby and a close approach to Halley's Comet, following a space shuttle launch in mid-1985. The encounter would be in about November 1985. The meeting with Tempel 2 would be nearly two years later and is less critical. Halley's Comet only appears near the Sun every 76 years and is one of the biggest comets known. Its approach in 1985 is a chance to look at a bright, young comet which may not be repeated for decades. Old, dim comets like Tempel 2 and Encke are much less difficult to find. The plan involves a small probe leaving the main flyby spacecraft and passing within about 1,500 km of the comet's nucleus, taking a cross-section of its dust and gas content as it goes.

The problem is that the small probe would be driven by an electric motor, powered by sunlight, and solar electric propulsion funds were in doubt at the start of 1980. Without them, the comet probe is pretty well dead, and later schemes to land on the nucleus of a comet, the surface of which would probably be very weak, are also made less likely. But the USSR, which has carried out electric propulsion experiments in space, may be interested in a mission like the NASA ESA one.

The asteroids and comets are a tempting target for astronomers, since although they do not contain an appreciable part of the mass of the solar system, they have been there, most likely, since the time the planets were formed and – unlike material which has been reworked by planetary geological processes – they are probably in almost exactly their original state before the solar system was formed. The decision on whether to take a close look at Halley's Comet may have been taken by the time this book appears, but it would be appropriate if it were the first comet to receive a man-made space probe. It was Edmund Halley who first made comet-spotting a science by realising

that the great Comet of 1680 was the same as the one seen early in the eighteenth century, and predicting that it would be back in 1758. It has come round every 76 years since, and records have now come to light of every apparition but one of Halley's Comet since 163BC, including its baleful appearance before the Battle of Hastings in 1066.

The other big objective in the solar system to which space scientists are turning attention is the Sun. The Sun supplies the energy to keep most of the rest of the solar system operating (the Earth's ocean currents and winds, for instance, are in effect a giant solar-powered steam engine). It also contains the huge bulk of the solar system's mass and energy. The Sun weighs about 330,000 times as much as the Earth. Even Jupiter, with over 300 times the Earth's mass, is small fry by the standards of even a modest star like the Sun. The Sun has long been observed from Earth's satellites, and the USSR, for instance, is actively using sounding rockets to examine short-wave radiation from the Sun, as well as examining the Sun and its atmosphere from manned spaceflights. A knowledge of the Sun's radiation is important for a wide range of Earthly uses. For instance, it interferes with radio traffic so that there is a strong interest on the part of armed forces. The U.S. Air Force maintains an impressive Air Force Solar Observatory in New Mexico. Solar radiation also drives the world's weather, and it is possible in time that measurements of solar energy weather, and it is possible in time that measurements of solar energy arriving at the Earth – which varies with time – can be integrated into weather forecasting technique. Knowledge about the long-term variation of the Sun's radiation may also allow us to get a better understanding of the climatic changes which give rise to ice ages, and major changes in sea level. This sort of information can only be incomplete if it does not take account of the full spectrum of the Sun's radiation. And solar radiation is best measured from space.

But we are now entering the era when space probes may provide a wealth of fundamentally new kinds of data about the Sun, with a wealth of spacecraft to look at the Sun from closer up than ever before, from new angles and in new wavelengths.

These include the NASA, ESA International Solar Polar Mission, an ambitious scheme designed to tell us much about the solar system itself as well as the Sun. The objective of ISPM is to launch one NASA and one ESA spacecraft in 1983, or possibly early 1984, from the space shuttle's Upper Inertial Stage. They will be launched, confusingly enough, directly away from the Sun. They will be aimed in fact at Jupiter, whose gravity field will be used to tip them out of the ecliptic, the plane in which the orbits of the planets lie. After their encounter with Jupiter's gravity field, one spacecraft will head over the Sun's North Pole and the other over its South Pole. Each craft will have eight different scientific experiments on board, designed to carry out a wide range of investigations. As well as a close look at Jupiter, especially its radiation and magnetism, there will be surveys of solar particles in space, and the Sun's magnetism above and below its poles, and work on X-ray and cosmic ray astronomy. The use of Jupiter's gravity to send the two spacecraft on their way is vital to save fuel, and offers the chance of a close look at Jupiter, but means that there will have to be shielding to protect the spacecraft instruments from Jupiter's magnetic and electrical fields. The whole mission, for which Dornier and TRW are prime contractors for the ESA and NASA spacecraft respectively, should take about five years from the launch for the two spacecraft to reach Jupiter, pass above and below the Sun, and run out again to the orbit of Jupiter, 778 million km from the Sun.

ISPM is a spectacular mission designed to answer many astronomical questions about the Sun – whose poles are almost invisible from the Earth – and about zones of space where no spacecraft has yet gone. But there is still mileage left in more traditional space exploration investigation of the Sun, typified by the 1981 Solar Maximum Mission being co-ordinated by NASA. In 1980 and 1981 the Sun is at the most active point in its 11 year cycle – sunspots will be at their maximum and so will, for instance, the Sun's interference with radio transmission, and the appearance of the aurora above the Earth's poles. This is caused by charged particles from the Sun interacting with the Earth's atmosphere, usually at about 150 km above the Earth's

surface. The particles are 'funnelled' into the polar regions by the Earth's magnetism. The NASA Solar Maximum Mission will involve a satellite to measure solar flares – violent eruptions at the Sun's surface – at X-ray, ultraviolet and gamma ray wavelengths. There will also be precise measurements of the Sun's radiation to determine whether fluctuations in solar heat output can effect the Earth's weather. The SMM satellite – which may be retrieved after use by a Space Shuttle mission – is part of a programme which also involves rockets and ground-based observations.

At the moment, although optical and radio telescopes have already been flown on a range of scientific satellites, the Space Shuttle is expected to make real observatories in space a reality. The Space Shuttle is expected to launch NASA's $500 million Space Telescope in 1983. Although the telescope's mirror will be only 2·4 m across, it will be able to see faint objects invisible from even the largest optical telescope at the Earth's surface, a 6 m telescope in the Caucasus. Later on, there could be an ESA telescope in space, launched by the Ariane launcher and tentatively named Hipparcos after an astronomer of Ancient Greece. Hipparcos would be designed for astrometry, the accurate measurement of star position. Like seeing faint objects, this should be much more of a proposition from above the Earth's turbulent atmosphere. In the long term, the prospects for space telescopes are limited only by what space technology can deliver. Dr Harvey Richardson, a Canadian astronomer, was reported in the *New Scientist* in 1979 as proposing that a Space Shuttle armed with a gas cylinder and a stock of liquid plastic could make telescope mirrors of anything up to 125 m across, although one would work up from, say, a 1 m prototype. They would be produced by cunning blowing – a hard plastic bubble could be made in a perfect parabaloidal shape, according to Richardson, such as earthly opticians have to struggle for years to produce with glass. Then a thin coating of aluminium would provide the reflective surface.

The other major Space Shuttle development which is bringing practical science in space closer is taking place in West Germany, where eight companies – with help from

other firms in nine European countries – are developing Spacelab, a science laboratory designed for a launch from the Shuttle. Astronomy, space physics, biology and earth observation account for 22 of the 62 experiments which the first Spacelab flight is expected to carry in 1981 at the earliest – the rest are all related to materials science.

The other major field of astronomy which stands to gain from space exploration is radio astronomy, which is beginning to open up in space just as increased use of radio airspace on the Earth – and by satellites – is endangering surface-based radio astronomy. A radio telescope was used by the Salyut 6 cosmonauts in 1979, having been brought to them by a robot freighter, Progress 7. It was used for radio examinations of the centre of our galaxy. At least some of the experiments carried out with the telescope involved using it as one of a pair with a big radio telescope in the Crimea. The two telescopes could be up to 100,000 km apart, allowing the effect to be created of looking at the sky with a radio telescope dish as big as the Earth itself.

The Salyut 6 radio telescope – which was unfolded like an umbrella once it had got into space – may be the precursor of a much more elaborate space radio telescope being planned by Soviet radio astronomers. They have got down to detailed engineering planning for a pair of radio telescopes from 1 to 10 km across, one of which would orbit the Earth. The other would be placed some 1500 million km out from the Sun, in an orbit around Saturn. The pair would use the same system of 'aperture synthesis' to create the effect of a large radio telescope as the Salyut radio telescope and its partner in the Crimea. (The same technique is in use widely between pairs of radio telescopes on Earth). The resolution would be vastly higher, by hundreds of thousands of times, than can be managed from Earth. So it would be possible to examine planets or other stars than the Sun for signs of life. Massive schemes like this would involve either people or robots – or both – in assembling large structures in Earth orbit, although it is possible that the Earthly end of such a radio telescope pair would be built on the Moon's far side to avoid interference from Earth. With radio astronomy literally driven from the face of the Earth by interference, radio astronomers in

Britain are pressing strongly for limits on the radiation which is allowed to leak from microwave ovens, which is probably already interfering with radio astronomy.

Space is also a good place to find out more about the Earth. Remote sensing, the science of looking at the Earth from space, is now highly-developed, and extends into weather forecasting, mineral exploration, and many other branches of the earth sciences. That sort of use for satellites is a branch of 'space applications' which is already paying dividends. But satellites are also being used to answer scientists' questions about the Earth and its relationship to the rest of space. This sort of research is as old as space exploration itself — one of the first and most important scientific discoveries made in space was the Van Allen Belts, layers of charged particles trapped by the Earth's magnetic field from hundreds to thousands of kilometres above the Earth's surface. Later satellites used to examine particles and fields around the Earth include the European Geos series, the first two of which were used in investigation of the Earth's magnetic field in space. A third Geos is being contemplated which would use fundamentally the same satellite as Geos 1 and 2, but be positioned in an orbit at a great distance from the Earth, perhaps around the Moon.

Another Earth exploration satellite already in orbit, if that is the right term is ISEE, the International Sun Earth Explorer, which has been placed 1·5 million km from the Earth at a stationary point where the pull from the Sun's gravity is just matched by that from the Earth and Moon. ISEE 3, another joint NASA ESA scheme, was launched at the same time as ISEE 1 and 2, placed in conventional Earth orbits to carry out the same sort of investigations as ISEE 3, on magnetic fields and particles in space, especially the solar wind, the constant stream of particles being blown from the Sun throughout the solar system. The ISEE spacecraft design is also to be used for the NASA ESA International Solar Polar Mission described above. Other earth science satellites now in use are looking at the Earth's heat input and outflow, and at the details of magnetic and gravitational fields.

In case that all seems a little abstract, the last thing we can investigate in space is ourselves. Man was preceded

into space by a parade of monkeys, dogs and other experimental animals, and these are still in use, as is man himself, in biological experiments in space designed to investigate the problems and advantages of living in space and to answer questions about life back on Earth. One of the Spacelab proposals, for instance, is for an experiment called the Space Sled, designed to test human response to weightlessness. It will operate by subjecting astronauts – probably European ones - to a range of accelerations and testing their reactions. Other life science experiments going on in space involve radiation resistance - a topic of increasing topicality back on Earth – which is being investigated by a series of Soviet Vostok experiments involving rats (and the first attempt to make animals breed in space, carried out in 1979), quails, and vegetable tissue as well as bacteria. The main aim is to look at the effect of weightlessness. US biological research in space is more or less at a halt for lack of money, but once Spacelab is going, there are plans for a dedicated Spacelab biology flight every two years, and to put biology experiments on Spacelab flights in between. How soon real benefits in terms of new crops, new medical techniques or new knowledge might result is hard to foresee.

7 Industry

If space is going to be an important social and economic factor for mankind, there have to be full-scale industrial activities going on there. Satellite communications, remote sensing and even warfare are going to be comparatively big business in space – perhaps they already are. But what is required for space expansion is genuine space industrialisation, involving the raw materials, energy, manpower and all the other features of earthly industry, adapted to space conditions.

An industrial base in Earth orbit does not exist yet: it would be surprising if it did. There are straws in the wind – one recent example is the Soviet announcement that crystals grown in space are used in electronic devices produced in the USSR. But the volume of such crystals manufactured in the Salyut 6 space station must be very small even by the standards of electronic components. Probably most of these space crystals are used in military hardware; electronic gadgetry for aircraft – and perhaps spacecraft – where weight and sophistication are both at a premium. Space products will probably always be premium products – transport costs will see to that, except possibly in the case of energy from space. But if they are ever to be economically important, space products will have to be produced in bulk as well as at a good price.

Extensive studies are being made of the science, engineering and economics of space industrialisation. All these aspects are vital – space processes have to be physically possible, practical, and worth doing in economic or some other terms. But the last aspect is the most interesting. Nobody is going to set up industries in space because they can be set up – only because it is worth doing so.

Even to date, there have been many visible economic benefits of space programmes. Doing things in space is expensive: it results in a flow of high-technology contracts which are one of the few ways of keeping aerospace contractors away from building devices of destruction. A major survey carried out in Europe by the European Space Agency and the Theoretical and Applied Economics Department of the Louis Pasteur University of Strasbourg showed that ESA contracts worth just over $900 million ended up by bringing over $2,500 million of benefit to the recipients. Amongst other effects, the ESA contracts allowed the firms to sell new products to customers outside the ESA, increase their sales of existing ones, pay for production lines which might otherwise have been idle, and pay for research and development which might otherwise have been done to less effect. The West Germans seemed able to make their ESA contracts worthwhile to the tune of 3.2 times their monetary value. The British, Italians and French managed ratios of 2.9, 2.6, 2.5 respectively. Other countries managed an average of only 2.2. That says a lot for the strength of links between government, research, and industry in West Germany. ESA concluded that the benefits were greater than the total sums governments had put into space research. This could be taken to mean that the economic benefits of space activities had already become positive for at least part of the population of Europe. Presumably the same goes for the USA, although the very different way in which the Soviet economy works means that calculations like those of the Strasbourg economists cannot be transposed one for one to the USSR.

The Louis Pasteur University – especially its Professor J P. Fitoussi – takes the potential economic benefits of space seriously. It ran a major conference in Spring 1980 on the economic effects of space developments and other types of advanced technology. Papers read included one on Fitoussi's work on the economic effects of ESA spending, and a NASA paper on the consequences of NASA spending within the US economy and the narrower field of technological innovation in the USA. Also on the agenda were the cost benefit aspects of meteorology from space

and the possible European effects of space budgets for the 1980s. 'Space research and clairvoyance' also seems to have been involved, with a paper from a University of Virginia economist, which just goes to show

In the USA, not surprisingly, the economic effects of space budgets have been much more thoroughly documented, if only because the sums of money spent have been so much greater. Space research has often been regarded as no more than state aid for high technology industry. But the US space programmes for the 1980s have mainly been constructed, apart from their military component, in terms of economic benefit.

In 1978, the issue of the economic effect of NASA spending came to a head with a clash between NASA and the US government's spending watchdog, the General Accounting Office. NASA's economics consultants had produced a report showing that NASA spending had enormous economic effects throughout the US economy even before genuine space manufacturing had got under way. They concluded, for example, that if in 1975 the US government had increased NASA's budget by $1 billion and taken the money away from some other part of federal spending, it would have created 20,000 jobs more, reduced inflation and helped 21 assorted industries, many of them producing below capacity. If NASA spending was increased in the decade between 1976 and 1985, US gross national product could go up by $23 billion, and inflation and unemployment cut by 2 per cent and 0.4 per cent. The General Accounting Office, according to a *New Scientist* account at the time, failed to agree by a wide margin.

The GAO riposte to NASA's arithmetic pointed out that, if true, the implication was that 'all of the nation's productivity growth and more besides' was being attributed to NASA: if one removed the alleged effect of NASA spending, US gnp actually declined. The GAO argued with NASA's arithmetic and that of its consultant economists, pointing out that small changes in the assumptions behind the equations made drastic differences to the answers, so that it is possible to prove that NASA spending had no general effect on the US economy.

The key to massive space industrialisation with big

economic benefits (bearing in mind that economic benefits accrue to individuals, governments, or firms, not to the world in general) seems to lie in developing large manned platforms for space activities which can be used as a base for space developments and allow financial and organisational economies of scale. Cheap transport to and from space is also vital. Space platforms are being examined as potential homes for every possible space activity from radio astronomy to synthesising medicines so that they are mentioned in practically every chapter of this book Experiments already carried out on docking spacecraft and manning them for lengthy periods indicate that there could well be something in the idea if the price is right. The problem is that everyone, especially in the USA, was waiting, as this was being written, to see how the space shuttle developed before thinking about the next generation of space structures. The space shuttle's performance is vital in calculations on the amounts of material which can be placed in orbit over the next decade and the price at which it can be done. Although there seemed to be little doubt early in 1980 that the Shuttle would fly, the price at which it would do so had been taking off with much more enthusiasm than the Shuttle itself, with an effect on the economics of projects dependent on it.

The importance of transport in future space developments was spelt out by John H. Disher, director of advanced programmes in NASA's Office of Space Transportation, in a 1979 paper in *Astronautics and Aeronautics*. Disher was Deputy Director of the Skylab programme, and is an authority on both jets and rockets. He thinks that the 1980s will see a 'build up of vehicles and services to meet commercial, scientific and industrial needs' in space.

The Space Shuttle and its Inertial Upper Stage and Spinning Solid Upper Stage, the latter two designed to take people and materials from low orbits to geostationary ones, or away completely from the Earth's gravity, are obviously vital parts of future space systems. But other components are satellite services, involving deploying, maintaining and retrieving satellites, and the space platforms themselves. NASA is active in all these,

according to Disher.

He says that US space platform plans will evolve gradually through the 1980s. Spacelab, the European space science laboratory, will start the process in the early 1980s. By 1983, large solar power arrays will be supplying power as Spacelab and other missions become more ambitious and the Space Shuttle Orbiter's fuel cells become unable to supply missions' power needs. Even then, missions will only be able to last 20 days according to Disher – still short of what Salyut 6 has already done. By 1985, these extended sorties would be followed by dedicated science and materials experiments platforms, and then a terrestrial observatory, a life sciences platform and a public services platform, the first real commercial application for Shuttle-launched platforms. The power problem is what NASA seems to want to solve first, which it is doing with power modules designed to allow first 20 and then 60 day flights. The 60 day missions will involve the massive 25 kW Power Module, a high solar sail dwarfing the Shuttle Orbiter itself. It can even be flown separately with experimental packages attached.

Disher thinks that science and applications platforms will get an experimental start with Spacelab and the Shuttle Orbiter. 'Generally speaking, the mode of operation would be to prove out sensors and equipment on Shuttle sortie flights and then transfer the payloads to free-flying platforms, with periodic Shuttle attendance for maintenance.' A general purpose, low level orbit inclined at 57° to the Earth's equator will do for most of the missions now being considered, although with more energy input – in other words, less payload per dollar – there can be other orbits including geosynchronous ones. 'Many missions for Earth observation will need near-polar orbit for complete Earth coverage. Such missions can be expected to evolve to specialised platforms in high-inclination orbit.'

NASA anlysis, according to Disher, has also extended to the 'Analysis of the cost of performing systematic, sustained materials processing in space research.' The research has shown, as might be expected, that 'longer stay-time in orbit together with more power to run experiment apparatus can significantly reduce the unit cost of

research.' By 1986 (in Disher's 1979 paper – the date will probably be later because of Shuttle delays since he wrote) there could be Materials Experimentation Carrier, MEC I, powered by the 25 kW Power Module and operating on an automated basis. It would take the form of a pallet docked to the power module. So far, space materials experiments have been on a small scale – the MEC would 'permit an orderly transition between the early exploratory research and later R & D programmes that capitalise on results from them.' The next stage, MEC II, is also being designed. Here there could be up to 7.5 tonnes of materials being processed in up to 9 5 cubic metres of space. The most important attraction of space manufacturing is the chance to do things in zero gravity: according to Disher, MEC II could keep gravity at a millionth of Earth gravity for up to five days.

On this mission, there would also be 'man-machine interfaces to permit changeout, (probably NASA's answer to replacement) maintenance and repair of equipment on orbit' so as to allow things to proceed for up to a year without interference from the ground, with 'a mix of man-tended and automated operations,' designed to 'permit nearly continuous operation of MEC II and its equipment.' After these pilot plant operations in the later 1980s, materials-processing payloads will, according to Disher, 'increase in size and need more support, requiring evolution towards larger equipment packages and greater power levels.' Here the technological challenges really begin.

According to Disher, 'Although at first they can be expected to be carried into space as an integral assembly . . . platforms will soon reach a size calling for in-space assembly of many pieces, deployment or unfolding of complex assemblies, fabrication of structural elements, or combinations of these.' A NASA programme called Large Space Structures Systems Engineering is looking at all these needs and the tools, techniques, and materials which they will demand.

It seems that large deployable structures which can be got into space in the Shuttle and then unfolded are the best beginning. An example are several large communications

antennae in which the US Department of Defense and others have a strong interest. After this, genuine space assembly becomes a possibility, which would involve extensive testing before the manufacturing systems were used. The technique could include Shuttle-mounted beam-making machines, producing metal or composite beams for building into orbiting structures. By the end of the century, according to Disher, this sort of development will mean that space platforms will have been built with power requirements perhaps a thousand times the 25 kW of the Power Module. An intermediate 250 kW system, power system and its accompanying orbital platform, as well as a large specialised geostationary platform, have already gone some way at least in NASA design offices.

Such schemes as the materials-processing facility which Disher expects to be the first full space manufacturing plant will also reequire more advance transport than the Shuttle, according to Disher. A new generation of chemical and solar-powered electric space vehicles are being thought out. Chemical energy sources will dominate, he thinks, in transfers between different Earth orbits, with solar electricity powering interplanetary missions. In pointing out the economic benefits which all this could mean, Disher points to a Science Applications Inc Study carried out for NASA which reported in April 1978. It found that by 2010, there could be $75 billion a year of revenues from space industrialisation. The bulk of this would be from satellite communications, with $30–40 billion. But there would also be just over $30 billion worth of energy sales – how that might come about, we shall get to soon – as well as nearly $1 billion in materials. The smallest part of the cash flow, well under $1 billion, would come from activities classed as 'people' – mainly tourism, medicine and entertainment. But although that sector is small in money terms, it would in Disher's view be much bigger in terms of 'visibility' and hence important in creating general awareness of the importance of space.

The sort of large structures Disher describes are less than a decade away, so it is not surprising that many studies of the problems are now being carried out by US corporations. Vought Corporation has been working on ways of

assembling beam structures in space: 72 structural joining ideas were considered. The favoured assembly procedure, possibly involving snap-together metal joints, may have the engineering advantage of allowing fluids, electricity and other services to be piped along the centre of the hollow tubing. A Rockwell International study in 1978–79 showed that massive saving in weight could be made, at least in principle, by making materials in space serve as many as four functions at once. In space power stations, for instance, load-bearing parts of the structure could conduct electricity as well. The same materials might also be used as communication and control systems for the satellite. If the components are designed with sufficient elegance, says Richard L. Long of Rockwell, it should 'permit the disassembly and reassembly of these materials into new and advanced structures as needs change without incurring the costs of generating new materials or the costs of putting these materials into orbit.'

This advanced work has been done at the same time as contract work on beam-making (using both metal and composites), carried out by Grumman and General Dynamics, on space refuelling (General Dynamics again), and on large structures engineering (McDonnell Douglas). Rockwell's $500,000, 18-month analysis of space construction focussed upon a 50 × 100 m platform which could be placed into synchronous orbit – small enough to be a feasible test of the possibilities, but big enough to carry applications equipment like communications antennae, and viable as a test which could give rise to direct technology transfer to industry. There were also General Dynamics studies, carried out jointly with NASA's Johnson space flight centre, to find out the threshold at which it is worth starting to bring material from the Moon instead of the Earth for large space structures. This notion is seen by Gerard O'Neill as crucial to his space colonies ideas. In 1979, it seemed to General Dynamics and NASA that a construction rate of one big (10,000 megawatt) orbiting power station per year for 30 years would make it worthwhile installing the necessary equipment in space and on the Moon. O'Neill has designed and built prototypes of an electrical 'mass driver' designed to take material from

the Moon to Earth orbit It may be that the task can be done more cheaply by a gas driven system proposed by Gerald W Drigers of the Southern Research Institute in Birmingham, Alabama.

What sort of materials processing possibilities exist in space? Plenty, according to enthusiasts, who point to a number of successful experiments which have already taken place to show the potential Rocket and spacecraft experiments carried out by West Germany and the USA have already done metallurgy and ceramics in space, and the number of high-value materials which have been produced or treated in space, or with which the possibility has been studied, is growing. NASA has been actively looking for years for industrial partners to help it develop space materials processing – anyone coming in with NASA stands to receive cut-price space on the Shuttle, technical help, and joint research and development deals, presumably involving access to NASA's own laboratories

One of the first materials to be produced in space conditions was glass It may well prove possible to produce glasses and metals of unprecedentedly high quality in space, since they can be melted down without coming into contact with a container In an October 1979 rocket experiment, NASA scientists melted glass in a sub-orbital flight which provided five weightless minutes. The glass was held while molten away from its containment walls by sound waves the gadget is called an acoustic levitator furnace The flight was the sixth in a NASA Marshall Space Flight Center programme called SPAR Space Processing Applications Rocket. It also tested techniques for solidifying magnetic materials with preferrred directions, dictated by magnetic fields instead of gravity. The exotic composite materials which might thus be produced might easily find their major application in future spacecraft. There was also a test of forming a semi-conductor layer on a base material, which could have consequences for space manufacture of electronic components

Other US proposals have included making high purity metals in space. Like glass production, there have already been experiments (mostly carried out with British rockets) on the part of German and US teams. One of these has

already produced a new and promising form of the rare light metal Beryllium. Beryllium is a light metal with promise for aircraft components and other high value uses. But when cast on Earth, the metal is brittle and not very useful as an engineering material. The new form of the metal, produced by a mixed academic and industrial team from Pennsylvania, still has that disadvantage. But by producing it in zero gravity it was possible to make Beryllium with a powder of Beryllium oxide spread uniformly through it. If this can be done (which it cannot with gravity present) it should also be possible to spread uniformly through the metal an agent which will lessen the Beryllium's grain and make it less brittle.

The next big steps in space materials processing will probably be tied to Spacelab for the West, in any case. As early as 1978, NASA had signed 17 contracts for applications experiments to be carried out early in the Spacelab programme. Potential projects involved producing special types of latex, semiconductors, and other materials including glasses. The first Spacelab mission was due at the time of writing to fly 40 materials processing experiments including many involving zero-gravity furnaces. Materials processing was due to account for most of the 1981 Spacelab 1 experiments, way ahead of astronomy, remote sensing, physics and biology. But industrial experiments were due to be less dominant on the later Spacelab 2 flight, which was expected to fly thirteen, much larger, experiments, mainly astronomical.

The first two Shuttle loads dedicated to materials processing experiments are due to be flown in 1983 and 1984, after the experience of the first three Spacelabs. This is a low rate of activity set beside the large numbers of launches planned for communications satellites, scientific probes, and nebulous tasks to be carried out on behalf of the Department of Defense. One contributory factor in this state of affairs may be a 1978 report from the National Research Council in Washington which found that an emphasis on space materials applications would be misplaced, since economically viable possibilities for space materials processing seem, realistically, to be few.

The NRC report, viewed as 'tough' by NASA officials,

concluded that it could not locate any examples of 'economically justifiable processes for producing materials in space,' recommending that 'this area of materials technology not be emphasised in the (NASA) programme.' At that stage, NASA said that it had already taken NRC's objections on board, so that it will require both new data and a considerable new commitment to increase the US space materials efforts again. NASA pointed out at the time that it was already working on a joint venture with Dow Chemical and Polysciences Inc to both make and market latex spheres in space, intended as both an engineering and a marketing test for space manufacturing. NRC also found no reason to think that space-made electronics components were likely to have much significance as a saleable product. Instead of breakthroughs and new, startling materials (which Earthly designers, after all, have to learn to use properly) NRC thought that NASA should try to push space manufacturing forward slowly in small increments, with reference to other US agencies and outside bodies to determine just what specific products might be most useful. NASA claims that this is what it does already: the space materials experiments are not its own, by and large, having been suggested by other organisations including companies.

The only other country to have carried out extensive space materials experiments in orbit rather than on short rocket flights are, of course, the Soviets. Although these experiments have been under way for some years, they reached their highest level so far on board the Salyut 6 space station, in which about 30 different space materials were produced, especially with the Kristall and Splav furnaces and a glass-fusing kiln which, the Russians claim, was used for the first glass melt ever carried out in space.

The Salyut 6 experiments, some of which were carried out with material samples from France, produced pure crystals (for instance of Gallium Arsenide) as well as tin, aluminium and molybdenum compounds and – despite the NRC's misgivings – semiconductors again. Two 47 gram semiconductor samples were produced in July 1978 and the results looked at by both Moscow's Institute for Space Research and the Polish Academy of Sciences in Warsaw.

The Salyut glass experiments were the first designed to test whether it might be possible to make precise optical surfaces in space, resulting in the elimination of all the lengthy and complex grinding processes which are needed to get optics precisely right on Earth. This seems like a slim hope, given transport costs at their present level and the fact that the technology for producing good optical surfaces already exists on Earth.

One of the lengthiest test programmes so far on zero gravity technology has been a series of West German experiments (involving British Skylark rockets fired from a Swedish test range) in which several minutes of weightlessness can be obtained at the top of the rockets' flights to 200–300 km above the Earth. One such flight, called Texus, took place in 1978 on behalf of the West German Ministry of Research and Technology, and involved five materials experiments modules. Each had its own power supply, controls, and data collecting system. The experiments centred around smelting materials and handling them in space in their molten form. The furnaces were pre-heated to just below the melting points of the samples before takeoff: with real space manufacturing, cheap solar power would mean that energy was not a problem. The experiments included one which successfully produced a lead-aluminium alloy. In gravity, the lead sinks to the bottom so that one has to make aluminium tin alloys instead. These cost more and their properties are not ideal. There was also an attempt to produce an improved alloy for covering gas turbine blades. This could lead to improved turbine blades which would need less frequent replacement. It was carried on behalf of MTU, a leading West German engine builder. Space manufacturing could be a real economic possibility here because the material used for the existing turbine blades, which have a disappointingly short life in service, already cost $5,000 per kilogram in 1978. There were also experiments on electrolytic processes to deposit thin layers of metals on surfaces which need to be protected or made electrically conductive. This technique is so precise that it might be improved by being done under weightless conditions.

A 1976 book, *Kiln Building with Space-Age Materials*,

described one pleasing way in which the US space programme has already provided ceramics craftsmen with alumina-silica fibre materials designed to protect space vehicles from the heat or re-entry. These, in one early furnace, allowed fuel costs to be cut to a quarter, firing time to a third, and labour and material costs to a half of those when firebricks are used to provide insulation, by a partial replacement of firebricks by the fibrous insulating material. That sort of feedback from Earth to space happens all the time. It will be a long while, it seems, before the materials come from space as well as the ideas.

One exception may be biological materials. A possible space manufacturing technique which may ultimately have a lot of potential is electrophoresis, which uses very small electric currents to separate out the different components of colloidal suspensions, in which small particles of material, often of living origin, are suspended in a much larger mass of liquid. The technique is difficult to do with gravity present but could be a lot easier in zero gravity.

Early in 1980 McDonnell Douglas, one of the big US aerospace contractors, signed an agreement with NASA to take the technique into space once it has been sufficiently developed. McDonnell Douglas Astronautics and a US pharmaceutical firm will do research on whether the idea is feasible before it goes into orbit. The NASA McDonnell Douglas agreement is the first of what NASA hopes will be a series of 'Joint Endeavours' with companies interested in bringing space technology to commercial use. One material which electrophoresis could produce is beta cells, the cells which fail to function in the pancreases of diabetics. If rejection problems could be got round, they could be implanted to help avoid diabetes. There are many problems, though. Critics of the idea of space manufacturing would point out that a simpler solution might well be to remedy Western eating habits, which seem to be at least partly responsible for the plague of diabetes now affecting developed countries.

Perhaps it does not matter too much that it could be a long time before living and inorganic materials processed in space find major applications on Earth. It seems from figures like those produced by Science Applications Inc

and cited by Disher that satellite communications (from increasingly capable, cheap and large geosynchronous satellites) are going to be the dominant revenue producing business in space even at the end of this century and the early decades of the next. Although space materials are an option which engineers, doctors and others on Earth might find useful, they are not likely to be a major part of the dynamics behind man's expansion into space for many years. Space manufacturing may become important if and when space colonies with significant populations develop. They are unlikely to pay for themselves with a population of astrophysicists and telecommunications engineers, although both species will presumably be represented.

What Gerard O'Neill and other space colony enthusiasts propose is that the colonies should pay for themselves not by making a better integrated circuit but by solving all our energy problems at once. The surprising thing about space colonies is that the idea has already been thought through much further than its closeness in the future would seem to justify. The same goes for the idea of using space-gathered solar energy on Earth, from Solar Power Satellites, universally abbreviated to SPS.

The vital role which O'Neill has played in getting the space colonies idea taken seriously, or at least mocked by all the best people, has been taken for SPS by Peter Glaser, not an academic but Vice-President for Engineering Sciences of Arthur D. Little Inc., a US firm of management consultants whose contracts include many for the US armed forces and other voracious consumers of high technology.

The SPS idea is not complex, and does not seem to require too much technology which we do not already have. What it does need is cheap transport into space, even if, as O'Neill and others have suggested, lunar materials are used for large parts of the SPS. The real debate over whether SPS is a good idea centres around what is the best way to use solar energy. Supporters of the SPS idea think, by definition, that space is the best place to do this. By placing solar power satellites in geosynchronous orbits where they can receive the Sun's radiation and convert it into microwaves to beam to Earth, it is possible to avoid

many of the problems inherent in using solar power on Earth. The SPS can be in sunlight virtually all the time: on Earth, the Sun only gets above the horizon half the time at any one place, so that the Sun's energy has to be stored to be used properly. It tends to fall at the Earth's surface most abundantly at times when it is least needed. The same goes on an annual basis as well as a daily one – the energy arrives in summer and is needed in winter. The SPS would be in the almost unvarying sunlight of outer space – it is independent of the time of day or year at the spot on the Earth's surface to which the energy it receives is based. And because the Earth's atmosphere, which is opaque to some wavelengths of radiation and scatters others very severely, is not in the way, the SPS could intercept a much more intense solar energy input than solar collectors on Earth. The margin is surprisingly wide - about four times as much energy is available per square metre in orbit as the best ground site – a cloud free desert near the equator – receives.

The space end of the SPS idea would be a 10 × 5 kilometre spacecraft consisting largely of a rectangular set of solar collectors. The material used might be silicon, gallium arsenide, or some other semiconductor. The collector surface would be vulnerable to meteoroid impact and other dangers, but the SPS should still have a life of from 30 years to over a century, well ahead of a nuclear power station. The 50 plus square kilometre satellite would produce five gigawatts of power, as much as five good-sized power stations, and Glaser envisages that there could be about 100 of them, beaming power to different areas in all but the Earth's most extreme latitudes. This means a total power output of some 500 GW, about ten times the maximum electricity demand of England and Wales in the 1979/80 winter.

According to a paper read by Glaser at one of the Princeton Conferences on Space Manufacturing in 1979, there are two possible geometries for the 5 GW 'reference' SPS. One would have just over 50 square kilometres of silicon cells while the other would have half that area of gallium aluminium arsenide cells with 53 square kilometres of thin reflectors to concentrate the sunlight. Each design

would send its power to Earth by means of a 1 km diameter antenna, sending microwaves to be received by a 79 square kilometre elliptical 'rectenna' (an antenna which also rectifies the current for use) at the Earth's surface.

Glaser says that some 555 715 workers would be needed in space to build the SPS. Part of the construction would be carried out in low Earth orbit but the SPS would be finally assembled in a geosynchronous orbit. The 5GW SPS is not a minor project. It would need, according to Glaser, a 425 tonne lift rocket to put the major components into orbit, and an electrically-powered 'transfer vehicle' to take the structures built there to their geosynchronous position. There would also have to be 75-man 'personnel launch vehicles' to carry both people and urgent cargoes from Earth to the low orbit, and a 160-man vehicle, also capable of carrying 480 man-months of consumable goods, between the low and geosynchronous orbits. The vehicles and the people could be reused on further SPS projects, although if solar power from space is to build up rapidly there will presumably have to be more than one SPS team active at a time. The SPS would almost certainly involve more effort and expense even than building five nuclear or coal-fired power stations to deliver the same power and dramatically more than saving the energy by means of conservation. The advantages would start once the station was in use.

The SPS would, naturally, not provide free energy for ever, or anything like it. The cost of paying off the construction bill would see to that, and if it did not the need to maintain the solar collectors, and the klystrons or other electronic devices which would be used to turn the solar energy into microwaves would. (One scientist described this part of the system as 'thousands of microwave ovens with their doors open pointing towards the Earth' during a radio interview. He and his colleagues regarded the simplification as rather undignified, but I think it captures the thing nicely.) Present klystrons fail – microwave ovens break down. There would be so many of them in the SPS reference design that unless there is a marked advance in their reliability, a team will be scuttling constantly around the SPS replacing them. Some technological advances may

mean easier SPS maintenance, for instance, solid state microwave generators or even free electron lasers to produce the Earthbound beam. Either of these, like advances in solar collecting materials, could also reduce dramatically the amount of material to be transported into space for the SPS, and therefore transform its economics.

These economics are crucially dependent upon, for instance, the cost of building metal beams in space and of setting up the several square kilometre orbital construction camp which Glaser envisages in low orbit. This would need several accommodation modules for 100 personnel each. With a programme of only one SPS per year, 15 tonnes of raw material per hour would be used according to a paper which Glaser read to the Canaveral Council of Technical Studies in 1979.

Whether all this is worth doing depends on how the arithmetic is carried out. Glaser's calculations produce costs about the same as nuclear and coal-fired stations. Every rise in the price of coal or oil, and every fresh technical or political problem which nuclear power runs into, strengthens the SPS case, just as every energy-saving device brought on to the market in a world of dear energy weakens it. According to Glaser, the SPS would also offer advantages such as better land use (nothing but the rectenna sites and a few launch areas), and less climate modification (no air pollution) than nuclear or coal power can offer.

It would be interesting to see an analysis of Glaser's schemes by comparison not with nuclear fission or coal but with nuclear fusion – a similar large-scale electricity source which may, by the middle of next century, be a significant competitor for SPS electricity. Fusion and SPS devotees would argue about which idea is the more highly developed at the moment: both are still embryonic. It would also be useful to line up the SPS notion against wave power, or small and large scale wind and solar power. Even the small research budgets so far devoted to these since 1974 have shown that they may have great promise - the real competition for SPS may well come from them. In any case, there could be safety problems with the flux of microwaves through the atmosphere which SPS would involve – it

could exceed what some countries such as the USSR regard as safe. There is now pressure in countries like the United Kingdom for microwave safety levels to be reduced as evidence of damage to the nervous system from low levels of microwave increases. The SPS microwaves could also interfere severely with radio reception. There is also the objection that small countries would have trouble swallowing 5 GW of electricity. Even if they use that much, there are problems managing an electricity grid when one power station contributes more than perhaps 10 per cent of the

Sector	*Spending*	*Benefits*	*Ratio*
	(Millions of 1977 US $)		
Ground operations	52	161	3.1
Space Systems	209	643	3.1
Rockets and satellites	500	120	2.5
Data processing	74	181	2.4
Ground engineering	15	48	3.2
Testing and development	29	30	1.1

These Strasbourg University figures (which do not add precisely because of rounding and double counting) show how just over $800 million of European Space Agency contracts turned into well over $2 billion of economic benefits for the contractors. Similar figures have been produced for NASA contracts, except that in the USA the numbers are even bigger.

power it uses. Sudden unplanned 'outrages', more popularly known as breakdowns outside the electrical engineering fraternity, can be disastrous if the system depends on a small number of large power sources. (Laser power transmission might allow the output from one SPS to be sent to several small rectennas, not one large one.)

The SPS idea is taking off, especially in the USA where a 1979 Solar Power Satellite Research Development and Evaluation Act voted $25 million to assess the idea. A

pressure group, the Sunsat Energy Council, had been set up (President: Dr Peter Glaser) to push for the idea In Europe, British Aerospace is keen on the idea (it is a big builder of solar power arrays for existing satellites) and is leading a study on the SPS idea sponsored by the United Kingdom's Department of Industry Even Prince Charles has been heard being enthusiastic about the idea But there are no certainties about energy, especially into the next century, and as a way of bankrolling space colonisation, solar power satellites seem to leave plenty to be desired.

Reading List

There are two main ways of finding out about space developments; periodicals for news, and books for background. Periodicals first. The field is fortunate it is being served by McGraw-Hill's *Aviation Week and Space Technology*, one of the world's premier business publications, which was invaluable as source material for almost every chapter of this book. *AW & ST* is almost always well-informed, and so are its readers. But don't subscribe unless you want to know a great deal about space developments, not to mention aviation. (In particular, the details about launch vehicles in Chapter One came primarily from *AW & ST*'s Aerospace Inventory and Forecast issue of 3 March, 1980.

Other useful material on space appears in general scientific publications like *New Scientist* (IPC Magazines, London), *Scientific American* (Scientific American Inc., New York), and *Science et Vie* (Excelsior Publications SA, Paris), while *Flight International* (IPC Business Press, Sutton, England) has a spaceflight news page most weeks. Also outstanding is *Sky and Telescope* (Sky Publishing Corporation, Cambridge, Mass.) for all the astronomical aspects of space research. Science correspondents of major newspapers also produce some good things, as do the scientists' trade papers *Nature* (Macmillan Journals, London) and *Science* (American Association for the Advancement of Science, Washington DC). These are not for the lay person, but the AAAS has recently started to publish a popular magazine, *Science 80*. What it will be called in 1981 remains, at the time of writing, to be seen.

There are also technical journals. Long features (many surprisingly accessible) on space development, particularly spacecraft design, appear in *Astronautics and Aeronautics*, (American Institute of Aeronautics and Astronautics) and

in the *Journal* of the British Interplanetary Society, which also publishes a popular magazine *Spaceflight*. The BIS *Journal* also published, as a special supplement, the Daedalus feasibility study on interstellar travel mentioned in Chapter One. It cost £6 from the BIS at 27–29 South Lambeth Road, London SW8 1SZ, England.

Turning to books, one was outstandingly useful while this volume was being put together. It was the *Observer's Spaceflight Directory* by Reginald Turnill (Frederick Warne [Publishers] Ltd., London). The *Directory* is an astounding piece of work – a virtually complete guide to everything that has happened in the space age, and much which has yet to do so. It lay on my desk all the time this book was being written, and the temptation to lean on it excessively was usually acute. A new edition is sorely needed. Although Turnill's companion *Manned Spaceflight* (same publisher) is more recent, and just as authoritative, it does not cover unmanned satellites.

Other books which were useful on aspects of space developments include *Outer Space – Battlefield of the Future?* (Stockholm International Peace Research Institute), *Resource Sensing from Space - Prospects for Developing Countries* (National Academy of Sciences, Washington DC), *Russian Space Exploration - The First 21 Years*, by Julian Popescu (Gothard House, Henley-on-Thames, England), and *The High Frontier* by Gerard K. O'Neill (UK edition by Corgi). Intriguing looks at what space exploration has told us about particular nearby planets are to be found in *Mars at Last!* by Mark Washburn (Abacus), *The Moon Book* by Bevan M. French (Penguin), and *The Atlas of Mercury* by Charles A. Cross and Patrick Moore. The latter, published by Mitchell Beazley, is notable for the remarkable airbrush maps of Mercury produced by the late Charles A. Cross. The Space Shuttle has given rise to a number of illustrated books explaining it in much more detail than I have been able to here. A good example is *The Space Shuttle Handbook* by Kenneth Gatland, Mark Hewish and Pearce Wright (Hamlyn).

Next, two marvellous books about space ideas and space facts. *A Fire on the Moon* by Norman Mailer is that great

writer's high water mark. Setting out to be an account of the Apollo 11 mission, it finishes up as a dazzling look at man's uneasy co-existence with technology, as well as showing that great writing about dead planets is perfectly feasible. Freeman Dyson's autobiography *Disturbing the Universe* (Harper & Row) is a fine book by a fine man, full of lovely ideas about Dyson's image of our future in space, tied firmly to the human condition today. Well worth a read, like most of the books listed here I owe all of their authors a great deal. In addition, two useful books published shortly before this one are *The Rocket*, a huge and comprehensive look at rocket technology by David Baker, published in the UK by New Cavendish Books, and *The Radiant Universe* by Michael Marten and John Chesterman (Blandford), a spectacular volume of space photography. Also outstanding in space photography are the many NASA special publication volumes of pictures from US space missions.

Lastly, science fiction is an obvious medium for exploring space ideas which have not yet come to fruition. Two space fiction books which are good novels as well as being full of good science are *Colony* by Ben Bova (Magnum), set mainly on an O'Neill-type space colony, and *The Jupiter Theft*, by Donald Moffit (Sphere), the story of a manned mission to Jupiter, and the surprises it receives there.

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